RTO-MP-44
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RTO-MP-44

NORTH ATLANTIC TREATY ORGANIZATION

RESEARCH AND TECHNOLOGY ORGANIZATION

BP 25, 7 RUE ANCELLE, F-92201 NEUILLY-SUR-SEINE CEDEX, FRANCE

RTO MEETING PROCEEDINGS 44

Advances in Vehicle Systems Concepts and Integration

(les Avancées en concepts systèmes pour véhicules et en intégration)

Copies of papers presented at the Systems Concepts and Integration Panel (SCI) joint symposium covering: Symposium (A) on "Aircraft Update Programmes. The Economical Alternative?" and Symposium (B) on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles" held in Ankara, Turkey, 26-28 April 1999.

Published April 2000

Distribution and Availability on Back Cover

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The Research and Technology Organization (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote cooperative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective coordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also coordinates RTO's cooperation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of initial cooperation.

The total spectrum of R&T activities is covered by 7 Panels, dealing with:

- SAS Studies, Analysis and Simulation
- SCI Systems Concepts and Integration
- SET Sensors and Electronics Technology
- IST Information Systems Technology
- AVT Applied Vehicle Technology
- HFM Human Factors and Medicine
- MSG Modelling and Simulation

These Panels are made up of national representatives as well as generally recognised 'world class' scientists. The Panels also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier cooperation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Published April 2000

ISBN 92-837-0011-2

Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
45 Sacré-Cœur Blvd., Hull (Québec), Canada K1A 0S7

Symposium (A)
Aircraft Update Programmes.
The Economical Alternative?

(RTO MP-44)

Executive Summary

The general theme of the joint symposium held in Ankara, Turkey on 26 to 28 April 1999 was "Advances in Vehicle Systems Concepts and Integration." The Symposium (A) on "Aircraft Update Programmes, The Economical Alternative?" provided an opportunity to share NATO experience in the upgrade and update of aircraft, including rotorcraft. Focus was on three key questions: "What can and cannot be done economically?"; "What are the limitations extending useful life of aircraft?"; and "How can technological advances be integrated?". These questions were addressed from both technical and cost-effectiveness points of view at this symposium.

The symposium was structured in five sessions covering Cockpit, Sensors, Engine, Overview and Lessons Learned (Part I and Part II) and was concluded by a panel discussion. There were twenty four papers presented. Two papers addressed cockpit upgrades taking benefit of the numerous advantages of the man-machine interface and allowing optimized operational capabilities to reduce overall development costs. Six papers addressed sensors/avionics. Discussions in this session included digital terrain system, electronic warfare management, modular avionics architecture, computer symbolic generators, air-to-surface weapon delivery and multi-target air-to-air armament control.

Three papers addressed the engine upgrades which covered advanced turbine engines for helicopters and the PW150 turboprop for C-130. Thirteen papers gave overviews or addressed lessons learned covering fighters (e.g. F16 MLU), transports (e.g. Transall C-160), rotorcraft (e.g. H-1), and discussions on cost-process for deciding between a new system versus an upgrade program. One of the principal parameters on cost is aircraft commonality. Two papers and a Keynote Address on USN/USMC H-1 program highlighted the commonality of 85 percent between the AH-1Z and UH-1Y.

In summary, with regard to the symposium title, "Aircraft Update Programmes, The Economical Alternative?", the answer is a resounding YES as concluded by the panel discussion. With a new aircraft development program costing a factor of ten or more than an upgrade program, it is difficult to challenge the cost-benefit of aircraft update programmes. The shortcoming with upgrading an existing aircraft is that its useful life is extended another 20 years at most, whereas a new aircraft would usually provide double the life.

Symposium (A)
Les programmes de modernisation des aéronefs. La solution économique ?

(RTO MP-44)

Synthèse

Le thème global du symposium qui a été organisé à Ankara, en Turquie, du 26 au 28 avril 1999 est le suivant : « Les avancées en concepts systèmes pour véhicules et en intégration ». Le symposium (A) sur « Les programmes de modernisation des aéronefs. La solution économique ? » a fourni l'occasion de partager l'expérience de l'OTAN dans le domaine des programmes d'amélioration et de modification des aéronefs, y compris les aéronefs à voilure tournante. L'accent a été mis sur trois questions: « Qu'est-ce qui est faisable dans les limites imposées par la rentabilité ? » « Quelles sont les obstacles au prolongement du cycle de vie utile des aéronefs ? » et « Comment intégrer les progrès technologiques ? ». Ces questions ont été examinées du point de vue technique et du point de vue de rentabilité.

Le symposium a été organisé en cinq sessions comprenant le poste de pilotage, les senseurs, les moteurs, un tour d'horizon et les enseignements tirés (Partie I et Partie II). Le symposium s'est terminé par des discussions sous forme de table ronde. Vingt quatre communications ont été présentées. Le sujet de l'amélioration du poste de pilotage en tirant profit des nombreux avantages offerts par les interfaces homme-machine et en réduisant les coûts globaux de développement par le biais de l'optimisation des capacités opérationnelles a été traité par deux communications. Six autres communications ont porté sur les senseurs et l'avionique. Les sujets suivants ont été discutés lors de cette session : les systèmes de suivi de terrain numériques, la gestion de la guerre électronique, l'architecture de l'électronique modulaire, les générateurs de symboles, le tir des missiles air-sol et la commande des systèmes d'armes air-air multicible.

Trois communications ont traité de l'amélioration d'un turbomoteur avancé pour hélicoptères et du turbopropulseur PW150 pour le C-130. Treize communications présentaient un tour d'horizon et des enseignements tirés concernant des avions de combat (ex : F16 MLU) des avions de transport (ex : Transall C-160) et des aéronefs à voilure tournante (ex : H-1) ainsi que des discussions sur le calcul des coûts pour permettre de décider entre l'achat d'un nouveau système et l'amélioration d'un système existant. L'identité de conception des aéronefs est l'un des principaux paramètres coûts. L'identité de 85% entre l'AH-1Z et l'UH-1Y a été mise en évidence par deux communications, ainsi que par le conférencier d'honneur dans son discours sur le programme de l'USN/USMC H-1.

En conclusion, concernant le titre du symposium, « Les programmes de modernisation des aéronefs. La solution économique ? » les discussions en fin de séance ont conclu par un OUI massif. Etant donné que les programmes de développement d'aéronefs nouveaux coûtent au moins dix fois le prix d'un programme d'amélioration, il est difficile de nier les coûts-avantages associés aux programmes d'amélioration. Le seul point faible de l'amélioration d'un avion existant est que sa vie utile est prolongée de 20 ans au plus, tandis que la vie utile d'un avion neuf est d'au moins 40 ans.

Symposium (B)
Warfare Automation: Procedures and Techniques for Unmanned Vehicles

(RTO MP-44)

Executive Summary

The general theme of the joint symposium held in Ankara, Turkey on 26 to 28 April 1999 was "Advances in Vehicle Systems Concepts and Integration". The Symposium (B) on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles" provided a state-of-the-art summary on technologies used for unmanned military vehicles, their operation and their integration into mission systems and battlefield scenarios. Focus was on operational requirements for unmanned vehicles, ongoing design and development programs and experiences from laboratory testing, field experiments and real applications of unmanned vehicles.

The Symposium was structured in four sessions:

1. Operational requirements for unmanned vehicles
2. Integration aspects and mission management
3. Platform management and critical technologies
4. System concepts and mission experience.

The Symposium was concluded by a round table discussion. In total, twenty three papers were presented. Six presentations addressed operational requirements from different perspectives. Six papers described integration and mission aspects, ranging from signal processing for micro sensors to fully autonomous unmanned combat air vehicles. Five presentations addressed platform management and technology aspects. System concepts and mission experiences were discussed in six papers, covering unmanned tactical aircraft system concepts, surveillance unmanned aerial vehicles, a land vehicle and reports from field experiences with unmanned aerial vehicles (CL-289 and Predator). Round table discussions covered aspects of operational requirements, levels of autonomy and corresponding time frames, cost considerations and integration of vehicles and battlefield management.

The design studies, development programs and the field experience with unmanned vehicles (air, land and sea vehicles) provided a comprehensive picture of the requirements, capabilities and uses of such vehicles and also very useful information for future development programs. Cost and cost effectiveness aspects were discussed, but more practical experience, a much better data base and considerable analytical work will be necessary to obtain a clear picture. One other area of concern which was addressed at this symposium was the problem of the integration of unmanned vehicles into mission systems and battlefield scenarios, and their interoperability with other existing and planned "systems of systems". At this stage of the development of unmanned vehicles, the requirements for interoperability and integration probably do not yet receive sufficient attention. More work and more coordination is needed in the future in order to make sure that these systems work together properly in the NATO environment.

Symposium (B)
Automatisation du combat : procédures et technologies de véhicules sans pilote

(RTO MP-44)

Synthèse

Le thème global du symposium qui a été organisé à Ankara, en Turquie, du 26 au 28 avril 1999 est le suivant : « Les avancées en concepts systèmes pour véhicules et en intégration ». Le symposium (B) sur « Automatisation du combat : procédures et technologies de véhicules sans pilote » a fait le point de l'état actuel des connaissances dans le domaine des technologies utilisées pour la réalisation des véhicules sans pilote, de leur exploitation et de leur intégration dans les systèmes de conduite de mission et les scénarios de combat. Le symposium a mis l'accent sur les spécifications opérationnelles des véhicules sans pilote, les programmes actuels de conception et de développement et l'expérience acquise dans le domaine des essais en laboratoire, des expériences sur le terrain et du déploiement de véhicules sans pilote.

Le symposium a été organisé en quatre sessions :

1. Spécifications opérationnelles pour véhicules sans pilote
2. Aspects intégration et gestion de mission
3. Gestion de plates-formes et technologies essentielles
4. Concepts systèmes et expérience opérationnelle

Le symposium s'est terminé par une table ronde. En tout, vingt trois communications ont été présentées. Différents aspects des spécifications opérationnelles ont été traités dans six présentations. Six communications ont porté sur les aspects intégration et missions, allant du traitement du signal pour microsenseurs aux véhicules aériens sans pilote entièrement autonomes. Cinq autres présentations ont examiné la gestion des plates-formes et les aspects technologiques. Des concepts de systèmes et l'expérience opérationnelle ont été examinés dans six communications, couvrant les concepts de systèmes pour véhicules aériens tactiques sans pilote, véhicules aériens de surveillance sans pilote, un véhicule terrestre et des rapports sur des expériences sur le terrain réalisées sur des véhicules aériens sans pilote (CL-289 et Predator). Les discussions qui ont eu lieu lors de la table ronde étaient centrées sur les besoins opérationnels, les niveaux d'autonomie et les tranches de temps correspondantes, les considérations de coûts, l'intégration des véhicules et la gestion du combat.

Les études de conception, les programmes de développement et l'expérience sur le terrain avec des véhicules sans pilote (véhicules aériens, terrestres et maritimes) fournissent la description complète des spécifications, des capacités et des applications de tels véhicules, ainsi que des informations très pertinentes sur les futurs programmes de développement. Les aspects coûts et rentabilité ont été discutés, mais il faudra beaucoup plus d'expérience sur le terrain, une base de données plus complète et des travaux d'analyse considérables avant d'avoir une vue d'ensemble plus claire. Une autre préoccupation de ce symposium a été le problème de l'intégration des véhicules sans pilote dans les systèmes de conduite de mission et dans les scénarios de combat, ainsi que leur interopérabilité avec d'autres « systèmes de systèmes » existants et projetés. A l'heure actuelle, il y aurait lieu d'accorder plus d'attention au développement des véhicules sans pilote, ainsi qu'aux exigences en matière d'interopérabilité et d'intégration. Plus d'efforts et plus de coordination seront demandés à l'avenir pour assurer la synergie de ces systèmes au sein de l'OTAN.

Contents

† Paper not available at time of printing.

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Symposium (B)
Warfare Automation: Procedures and Techniques for Unmanned Vehicles

† Paper not available at time of printing.

Theme

The general theme of this joint symposium was "Advances in Vehicle Systems Concepts and Integration". Two simultaneous symposia were presented:

1. Symposium (A): "Aircraft Update Programmes. The Economical Alternative?"

   This symposium provided an opportunity to share NATO experience in the upgrade and update of aircraft, including rotorcraft. Focus was on three key questions: "What can and cannot be done economically? What are the limitations extending useful life of aircraft? and How can technological advances be integrated?" These questions were addressed from both a technical point of view and a cost-effectiveness perspective.

2. Symposium (B): "Warfare Automation: Procedures and Techniques for Unmanned Vehicles"

   This symposium provided state-of-the-art summary on technologies used for unmanned military vehicles, their operation and their integration into mission systems and battlefield scenarios as well as acquisition and system operating costs. Theoretical studies forecast cost reductions - "Is this supported by real experience?" Special attention is on joint missions of land/sea/air forces, in areas with highly automated and cooperative infrastructures and simple and hostile environments as well.

We believe the participants in this conference made significant contributions toward meeting the increasingly difficult challenges of the NATO nations' defense requirements within the limitations imposed by necessary economics in military resource allocations.

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Acknowledgements

The Systems Concepts and Integration Panel wishes to express its thanks to the National Authorities of Turkey for the invitation to hold this joint symposia in Ankara.

We would like to thank the Middle East Technical University for hosting the symposia in their campus and convention center and for providing the necessary logistic support.

We would like to thank TUBITAK, Turkish Scientific and Technical Council, for providing financial support for the symposia.

We would also like to thank:
ASELSAN (Turkish Military Electronics Industries)
ROKETSAN (Turkish Missile Industries)
TAI, TUSAS (Aerospace Industries, Inc.)
STF-SAVRONIK
TEI, TUSAS (Engine Industries Inc.)
for their support.

And finally, we wish to thank the following for their contribution to the success of these symposia:
European Office of Aerospace Research and Development
Air Force Office of Scientific Research
United States Air Force Research Laboratory
United States Office of Naval Research, Europe.

Keynote Address

by

M. Özsu
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It is a great pleasure for me and for my delegation to welcome you here in Ankara, in this pleasant campus of Middle East Technical University, on the occasion of the Spring Symposium of the System Concepts Integration Panel of the Research and Technology Organization of NATO. The topic of the present symposium, **Advances in Vehicle Systems Concepts and Integration,** is of particular importance for all of the NATO nations when a new century is only a few months ahead. As I understand, the present meeting is composed of two parallel symposia: one on the very important subject of **"Aircraft Update Programmes. The Economical Alternative?"** and the other on the subject of **"Warfare Automation: Procedures and Techniques for Unmanned Vehicles".** Both of these topics are of vital importance for all of the NATO nations which I believe are well represented within this audience by their competent scientists.

The subject of the first symposium; "Aircraft Update Programmes, the Economical Alternative?" is becoming more and more important when the increasing cost factors of new aircrafts are considered. Aircraft Technologies are developing very fast with more demanding requirements of the battle field operations. However all these developments have a cost which is becoming more and more important for the tight defense budgets of the nations. Hence updating / upgrading of the existing platforms with more advanced up to date new technology is becoming more and more an economical alternative.

- Structural Upgrades, including the utilization of newly developed materials, such as new composites are being employed on various aircraft, both fixed wing and rotary wing.
- Of course Avionics Upgrade/Update is a major field where all countries are involved. Electronics and in particular aviation electronics is one particular field where the most rapid technological developments are witnessed. Computer systems are becoming more powerful and more compact every day hence making even the most sophisticated and the fastest computers of today definitely obsolete within a very short time. Therefore, avionics update of very successful air crafts is a major issue in Turkey which I believe is also the case in other NATO countries. To name a few: F4, F5, T-38. Upgrading of the existing air craft with more advanced navigation instruments and modern radar systems is very important for their survivability in adverse flight conditions.
- Propulsion or Engine Update / Upgrade is another major issue. To obtain higher thrust per unit weight and to have more economical engines are the basic issues for propulsion upgrades. This brings also the strict and demanding requirements for the maneuverability of the aircraft in adverse flight conditions.
- One major issue is definitely the improvement of the flying and the handling qualities of the aircraft. As far as the problem of controlling the aircraft is considered, this is definitely one of the most important areas where upgrading and updating are needed.
- Electronic warfare is an another important issue which I believe will be addressed to a great extend during this symposium.

Paper presented at the RTO SCI Symposium on "Advances in Vehicle Systems Concepts and Integration", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

The subject of aircraft update and upgrade is very important for Turkey which I believe is equally important for our NATO allies. This symposium will definitely provide the appropriate platform for the exchange of ideas and experiences among the NATO nations.

The subject of the second symposium, "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", is also as important as the first one. The operational needs and the requirements for unmanned air vehicles have been widely experienced during the last Bosnia Operation and is being used extensively today in Kosova operations of NATO. All these operational aspects of Unmanned Vehicles have shown the vital importance of Warfare Automation and the procedures and techniques related to their utilization. The need for Unmanned Vehicles in the battlefield scenarios can not be denied. The concept of Aerial Unmanned Vehicles (Uninhabited Air Vehicles) can be extended to missions of land and sea using Unmanned Vehicles. In this respect the topic of the present symposium serves the purpose and the objectives of the newly formed Research and Technology Organization of NATO. Hence, the integrating nature of this panel have successfully integrated the operational needs of land/sea and air unmanned vehicles within the scope of this symposium.

The topics of the papers to be presented during this meeting changes from the Operational Requirements of the Unmanned Vehicles to their Integration Aspects and Mission Management, from Platform Management and Critical Technologies to System Concepts and Mission Experiences.

I am sure that we will all benefit and learn from the experiences of the other NATO nations during these two symposia. One of the major outcomes of these symposia is definitely the establishments of close friendships between different nations and the sharing of knowledge gained from the experiences of the others.

I hope that this meeting will be one of those meetings that you will always remember with good souvenirs. I welcome you once again to Turkey and ensure you that we will do our best to make your stay during this week a pleasant one.
Thank you.

Keynote Address

by

J. Thomas Curtis
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AIR ASW Assault & Special Mission
Program-USMC Light/Attack Helicopt.
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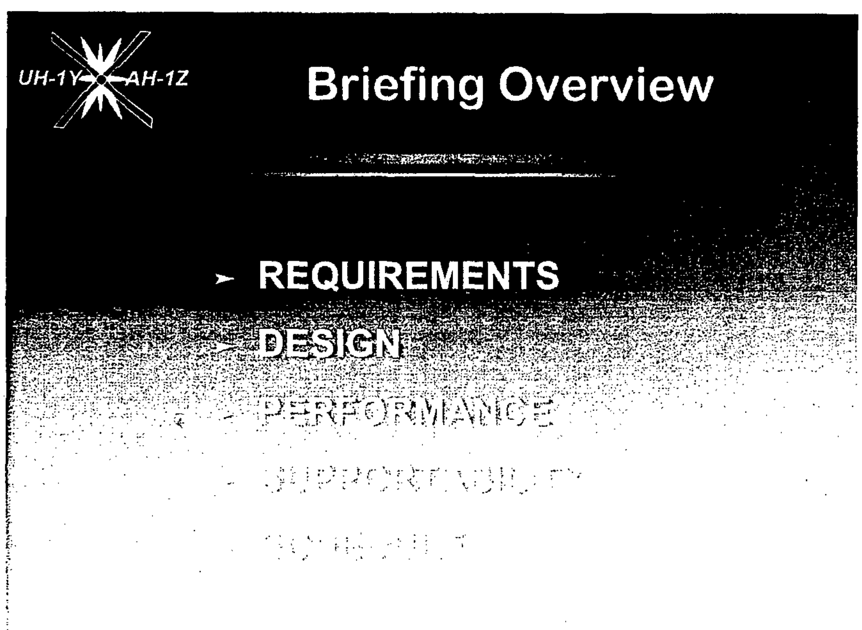
Patuxent River, MD 20670-1547, USA



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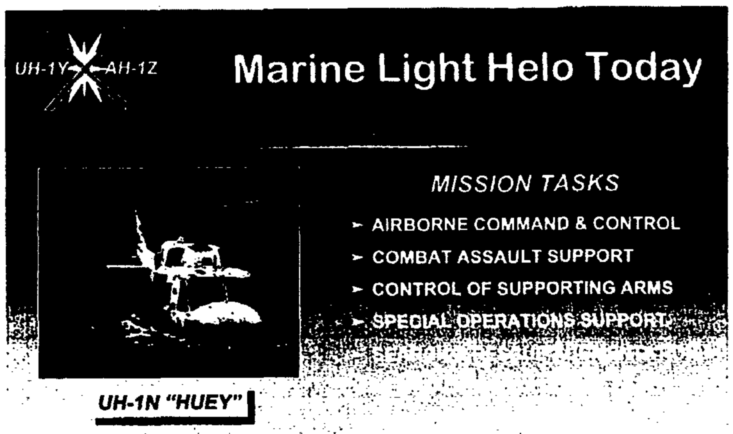
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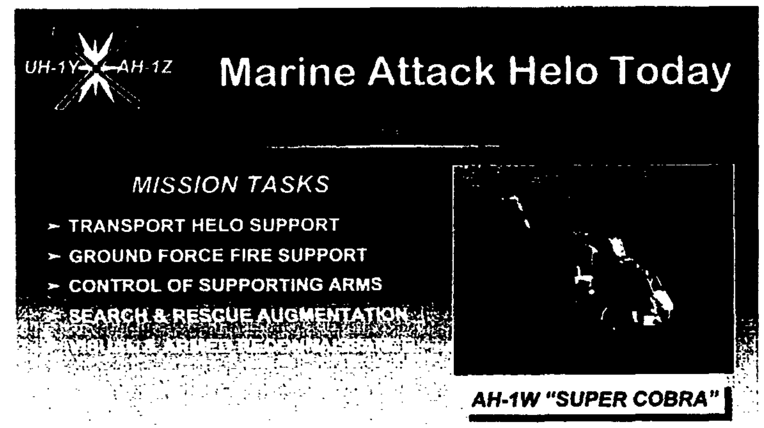
➤ COMBAT ASSAULT SUPPORT
➤ CONTROL OF SUPPORTING ARMS
➤ SPECIAL OPERATIONS SUPPORT
UH-1N "HUEY"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Marine Attack Helo Today
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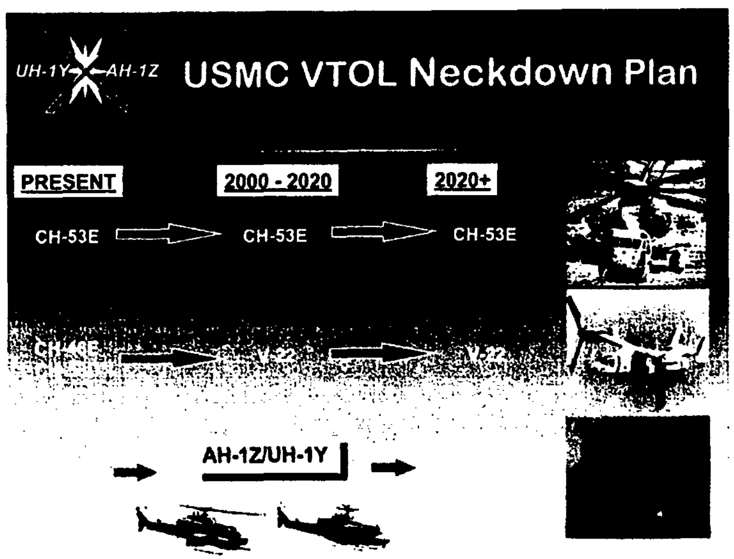
➤ SEARCH & RESCUE AUGMENTATION
AH-1W "SUPER COBRA"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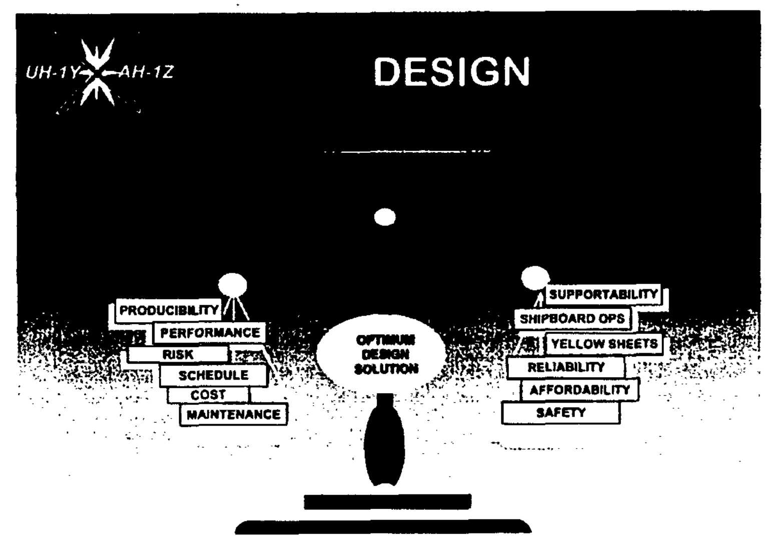
UH-1Y AH-1Z
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SHIPBOARD OPS
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AFFORDABILITY
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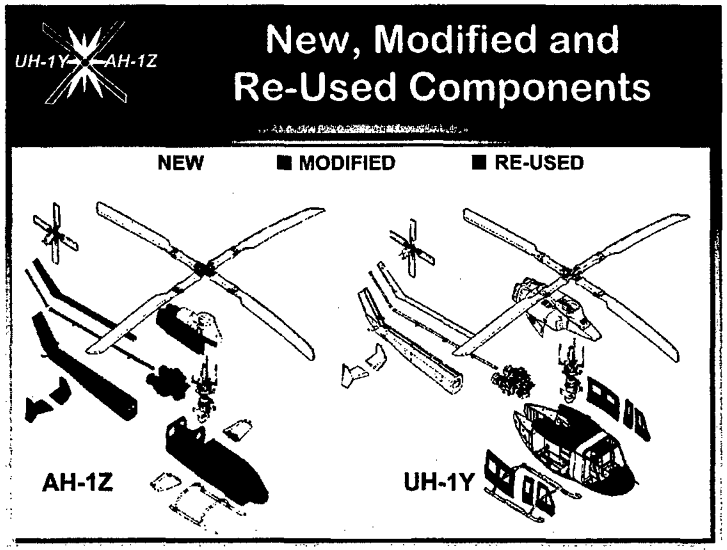
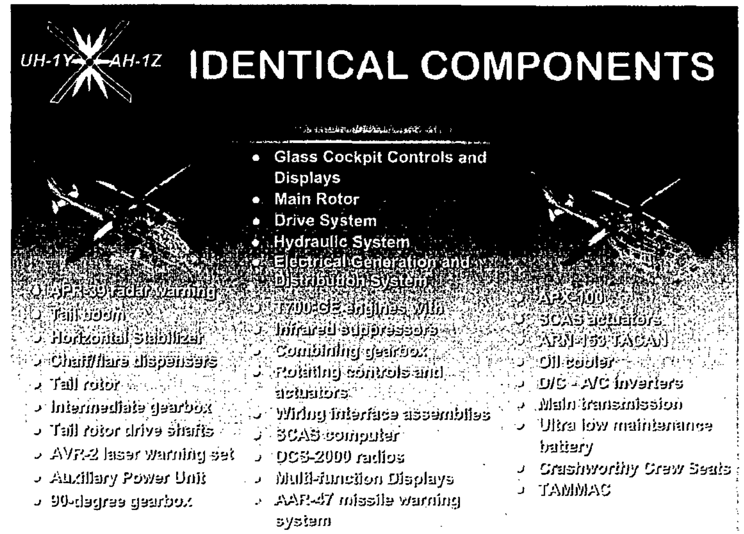

UH-1Y AH-1Z
New, Modified and Re-Used Components
NEW
MODIFIED
RE-USED
AH-1Z
UH-1Y


UH-1Y AH-1Z
IDENTICAL COMPONENTS
Glass Cockpit Controls and Displays
Main Rotor
Drive System
Hydraulic System
Electrical Generation and Distribution System
APR-39 radar warning
Tail boom
Horizontal Stabilizer
Chaff/flare dispensers
Tail rotor
Intermediate gearbox
Tail rotor drive shafts
AVR-2 laser warning set
Auxiliary Power Unit
90-degree gearbox
T700-GE engines with
Infrared suppressors
Combining gearbox
Rotating controls and actuators
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Multi-function Displays
AAR-47 missile warning system
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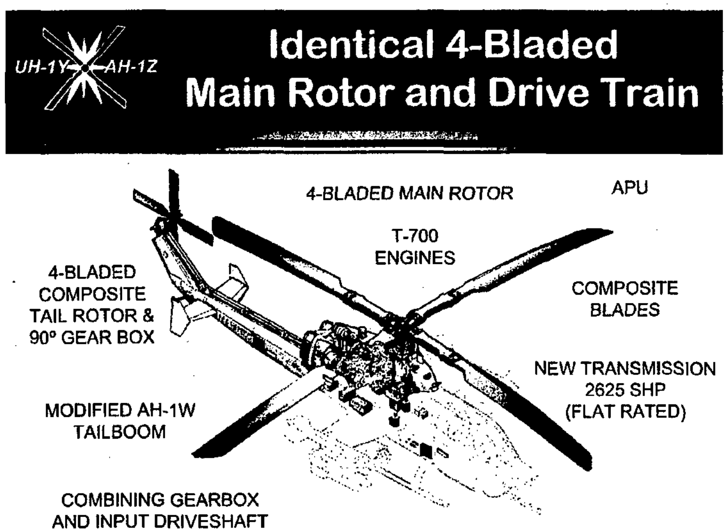
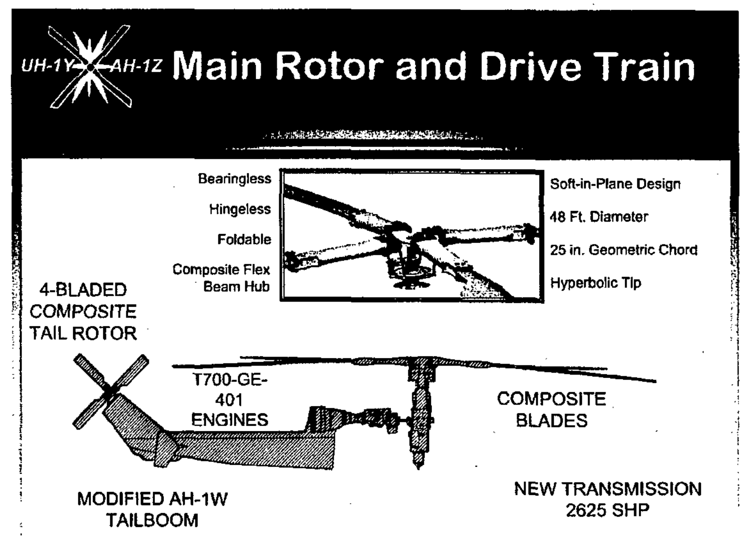
SCAS actuators
ARN-153 TACAN
Oil cooler
DC - AC inverters
Main transmission
Ultra low maintenance battery
Crashworthy Crew Seats
TAMMAC

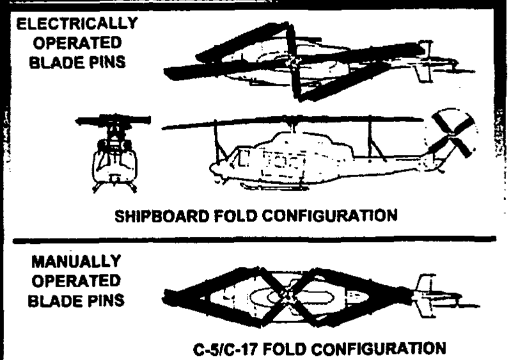

UH-1Y AH-1Z
Identical 4-Bladed Main Rotor and Drive Train
4-BLADED MAIN ROTOR
APU
T-700 ENGINES
4-BLADED COMPOSITE TAIL ROTOR & 90° GEAR BOX
COMPOSITE BLADES
NEW TRANSMISSION 2625 SHP (FLAT RATED)
MODIFIED AH-1W TAILBOOM
COMBINING GEARBOX AND INPUT DRIVESHAFT


UH-1Y AH-1Z
Main Rotor and Drive Train
Bearingless
Hingeless
Foldable
Composite Flex Beam Hub
Soft-in-Plane Design
48 Ft. Diameter
25 in. Geometric Chord
Hyperbolic Tip
4-BLADED COMPOSITE TAIL ROTOR
T700-GE-401 ENGINES
COMPOSITE BLADES
MODIFIED AH-1W TAILBOOM
NEW TRANSMISSION 2625 SHP

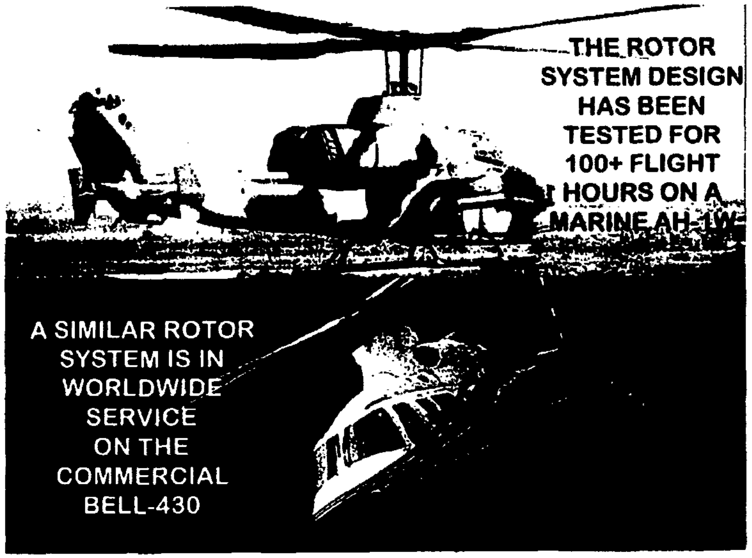
Common, Semi-Automatic Blade Fold for UH-1Y/AH-1Z

UH-1Y AH-1Z

- Blades Manually Indexed & Folded
  - Electrically Locked Blade Pitch
  - Folds In 45 Knot Winds
  - Spread or Folded to 70 Knots



SIMPLE, RELIABLE DESIGN REDUCES WEIGHT AND COMPLEXITY



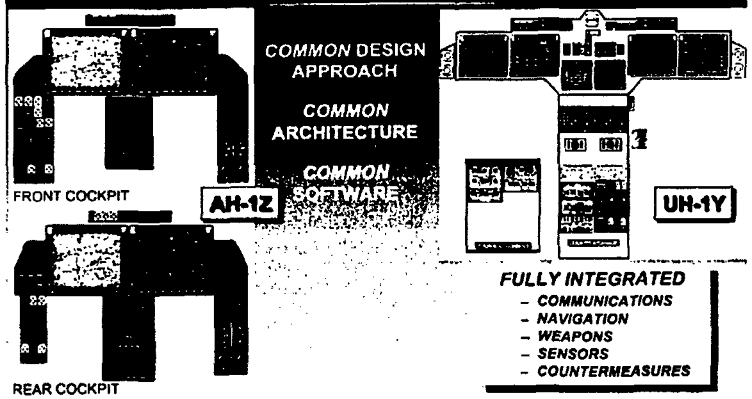
Vulnerability Reduction

UH-1Y AH-1Z

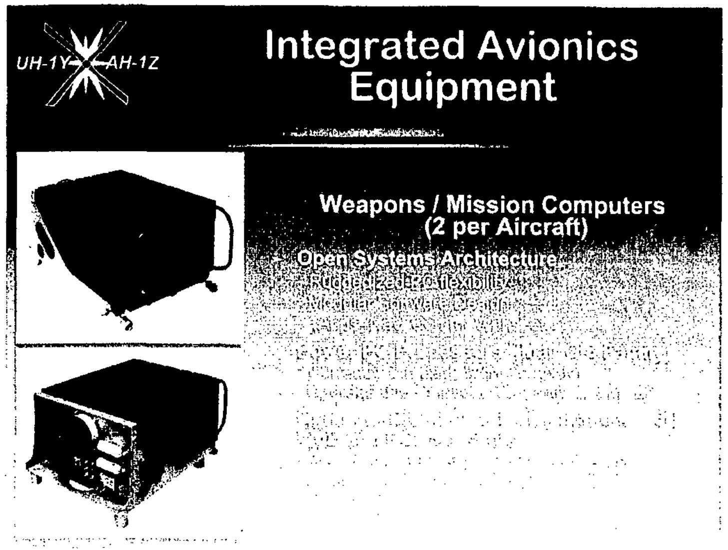
- BALLISTIC TOLERANCE
  - Main & Tailrotor to 23mm
  - Main Driveshaft, Mast & Rotor Controls to 12.7mm
  - Fuel System 12.7-20mm
  - Main/42°/90° Run-Dry Gearboxes
  - Crew Armor
- ENGINE IR SUPPRESSION
- FUEL SYSTEM PROTECTION
  - Self-Sealing Cells/Lines
  - Suction Fuel Transfer
  - Fuel Cell Powder Panels
  - OBIGGS
- REDUNDANCY
  - *Twin T700 Engines*
  - Dual Hydraulics
  - Dual Tandem Actuators
  - 4 DC Power Sources
  - Redundant Structure
- INTEGRATED EW SUITE
  - Radar/Missile/Laser Warning
  - 4 CM Dispensers
- CRASHWORTHY SEATS
  - Pilots
  - Troop Seats in UH-1Y

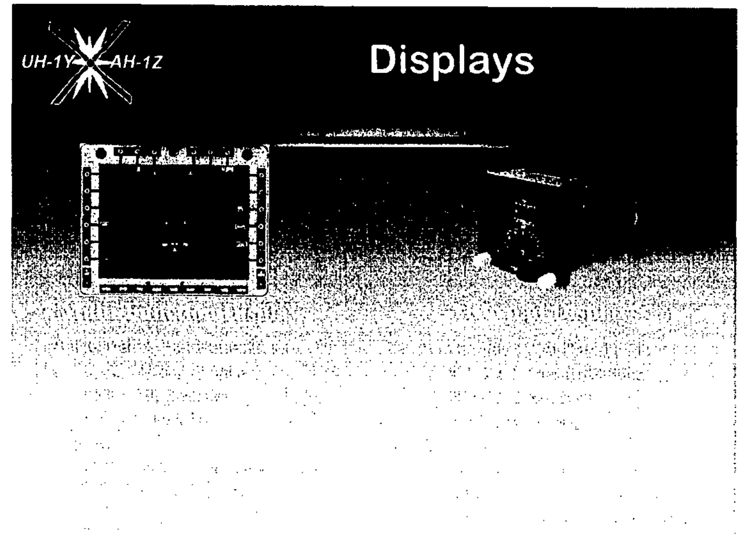
Integrated Glass Cockpits

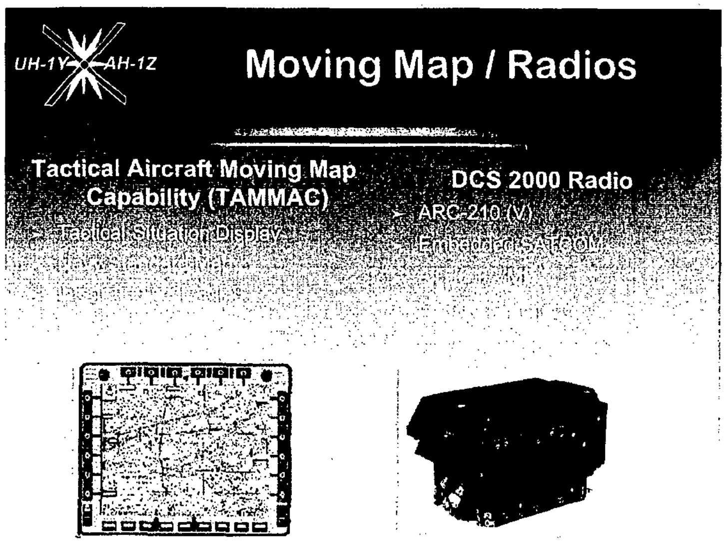
UH-1Y AH-1Z

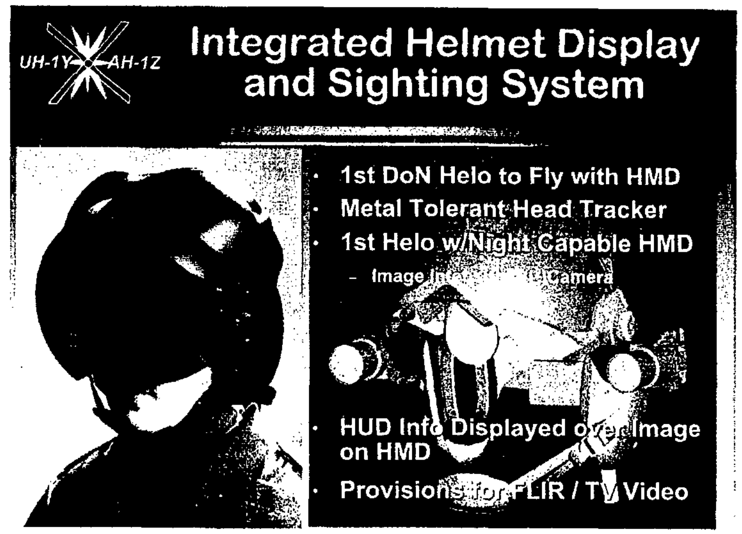


FULLY INTEGRATED
- *COMMUNICATIONS*
- *NAVIGATION*
- *WEAPONS*
- *SENSORS*
- *COUNTERMEASURES*


UH-1Y AH-1Z
Integrated Avionics Equipment
Weapons / Mission Computers (2 per Aircraft)
Open Systems Architecture


UH-1Y AH-1Z
Displays

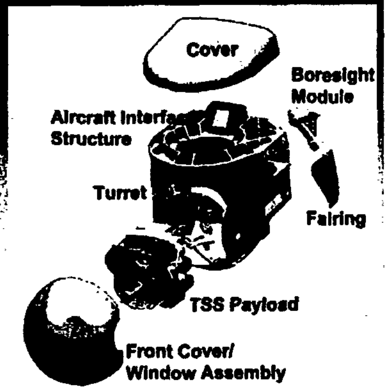

UH-1Y AH-1Z
Moving Map / Radios
Tactical Aircraft Moving Map Capability (TAMMAC)
Tactical Situation Display
DCS 2000 Radio
ARC-210 (V)
Embedded SATCOM


UH-1Y AH-1Z
Integrated Helmet Display and Sighting System
1st DoN Helo to Fly with HMD
Metal Tolerant Head Tracker
1st Helo w/Night Capable HMD
HUD Info Displayed on HMD
Video

TSS - An NDI System Leveraging DoD and Commercial Technology

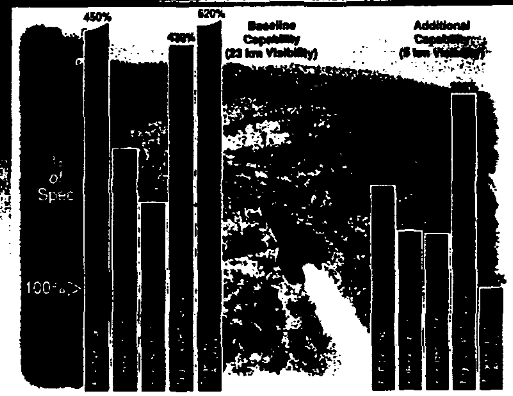
UH-1Y AH-1Z

- Superior Performance
  - 3rd Generation Optics
  - Unmatched Stabilization
- Open Architecture
  - Increased Reliability and Supportability



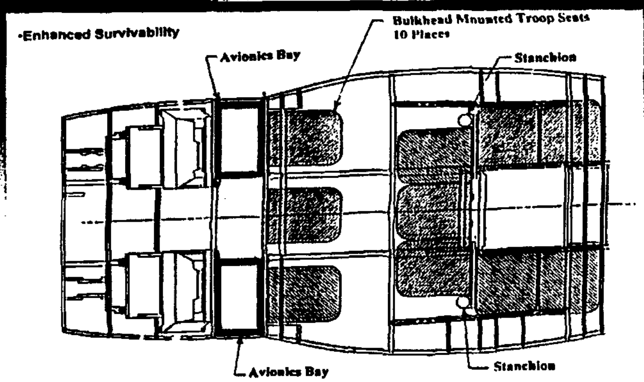
TSS Performance Assessment

UH-1Y AH-1Z

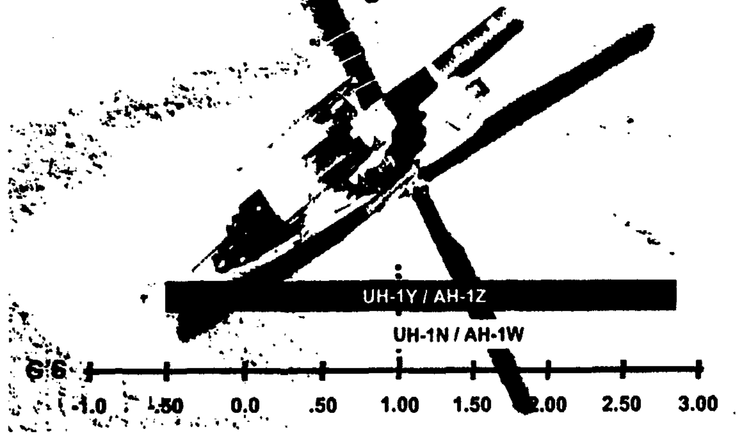


UH-1Y Crashworthy Seats

UH-1Y AH-1Z



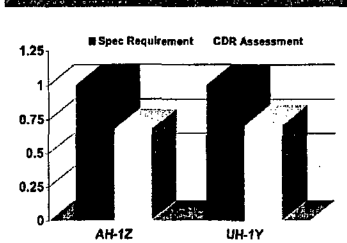
Improved Maneuverability



UH-1Y AH-1Z

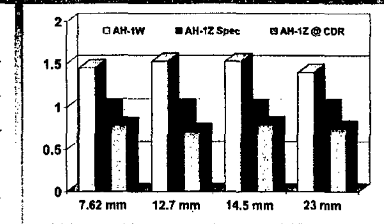
Increased Survivability

REAR ASPECT (LOOKING INTO EXHAUSTS)
NORMALIZED TO UH-1Y/AH-1Z SPEC



Reduced IR Signature

26 VIEW AVERAGE, HOGE
ARMOR PIERCING INCENDIARY @ 2500 fps

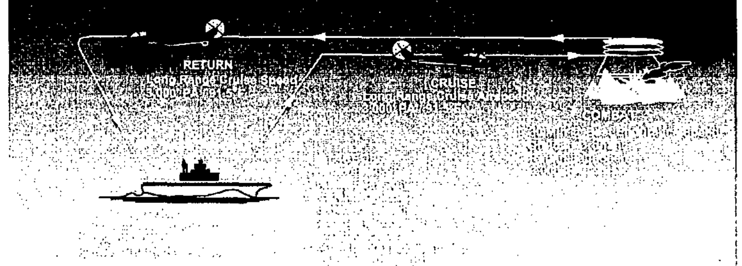


Reduced Ballistic Vulnerability

UH-1Y AH-1Z

AH-1Z Mission Profile

CLOSE AIR SUPPORT



110 nm Mission Radius

UH-1Y AH-1Z

AH-1W / AH-1Z Comparison

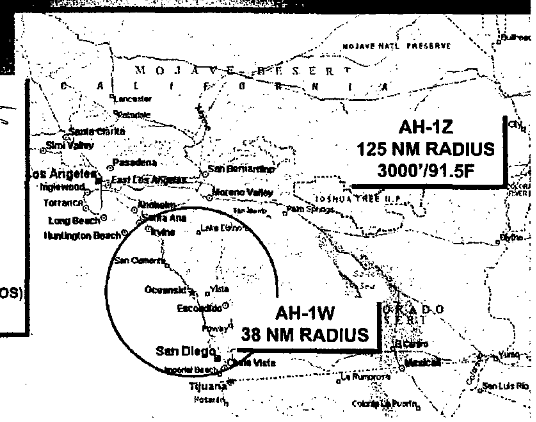
	AH-1W	AH-1Z
Empty Weight, lb	10,618	12,300
Max Internal Fuel, lb	2,086	2,858
[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]
Cruise Speed, kts	132	143
Weapons Stations	4 Wing Stations 2 Universal 8 PGM's	6 Wing Stations 4 Universal 16 PGM's
Mission Radius, nm w/2,500 lb Payload	38*	125

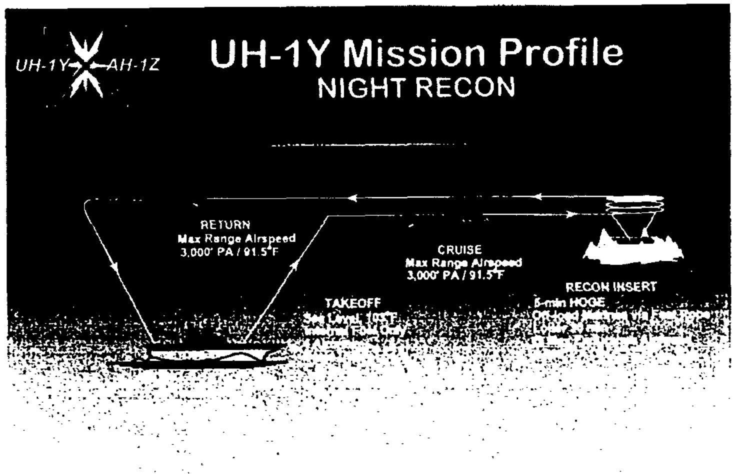
*AH-1W must download fuel to carry 2500 lb payload under these conditions

UH-1Y AH-1Z

AH-1W vs. AH-1Z CAS Mission Radius

8 HELLFIRE
14 ROCKETS
650 ROUNDS
30 MIN TIME ON STATION (TOS)
20 MIN FUEL RESERVE



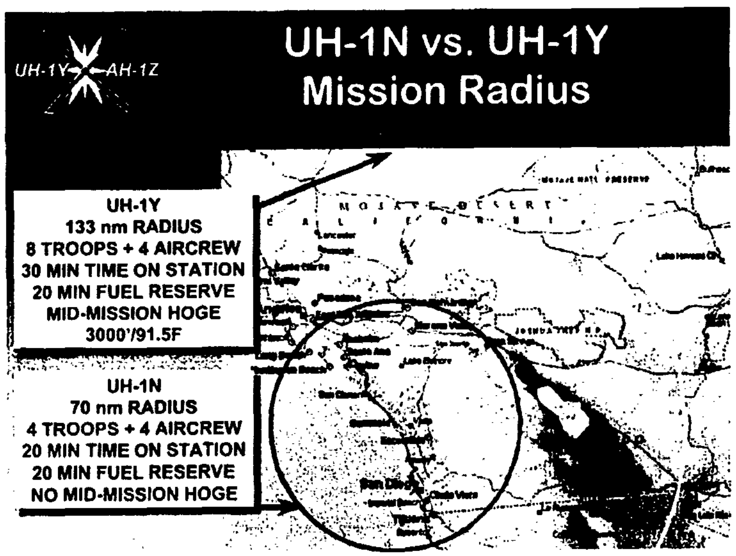


110 nm Mission Radius

UH-1Y AH-1Z

UH-1N / UH-1Y Comparison

	UH-1N	UH-1Y
Empty Weight, lb	6,708	11,565
Max Internal Fuel, lb	1,381	2,628
HOGE High/Hot Wt, lb	9,890	16,900
[illegible]	0	[illegible]
Weapons Stations	2 Hard Mounts	2 Hard Mounts
Mission Radius, nm w/2,800 lb Payload	0	133



SUPPORTABILITY

Top Readiness Degraders

UH-1Y / AH-1Z

AH-1W

Starter	New Design
Transmission	New Design
Batteries	Replaced
Attitude Gyro Indicator	Removed (EGI)

UH-1N

Tail Rotor Driveshaft Hanger — Change to AH-1W [illegible]

Drive Train Components

UH-1Y / AH-1Z

TBO = Time Between Overhaul
Life = Component service life

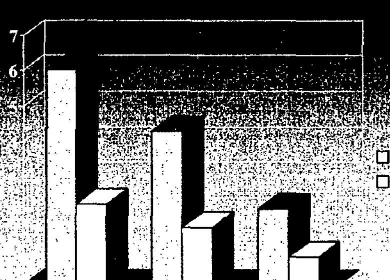
	AH-1W		UH-1N			
	TBO (hr)	Life (hr)	TBO (hr)	Life (hr)		
MAIN TRANSMISSION	1100		1800			
TAIL ROTOR GEAR BOX	1400		1800		[illegible]	
MAIN ROTOR HUB AND BLADES	1100	2200		2200		10000
[illegible]		[illegible]		[illegible]		10000
[illegible]		[illegible]		[illegible]		10000

ROBUST DESIGN + ON-CONDITION MAINTENANCE = "LIFETIME" ROTOR AND DRIVE TRAIN

Reduced Strategic Airlift Requirements

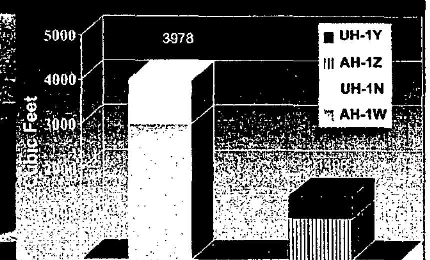
UH-1Y / AH-1Z

NUMBER OF AIRCRAFT REQUIRED TO MOVE 180 DAYS CSP/SE FOR ONE HMLA SQUADRON

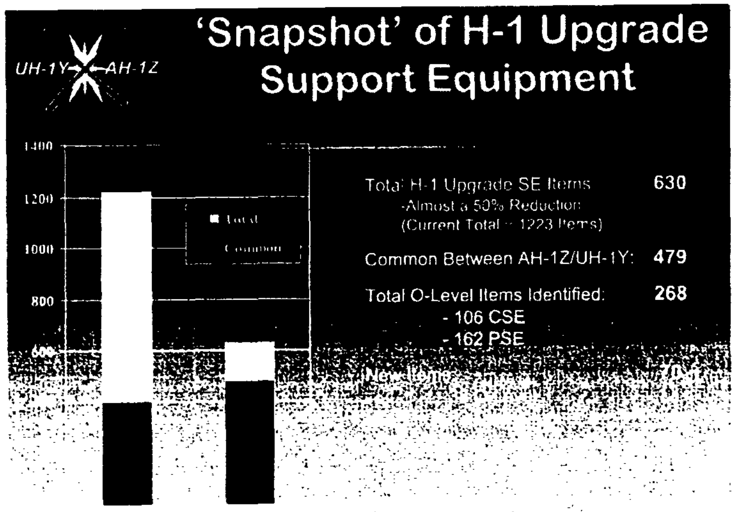


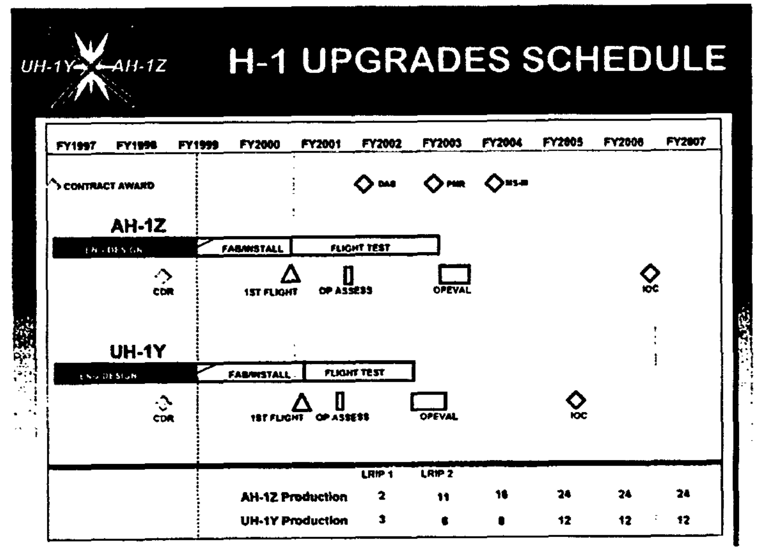
MEU 90-Day Spares Support Storage Requirements

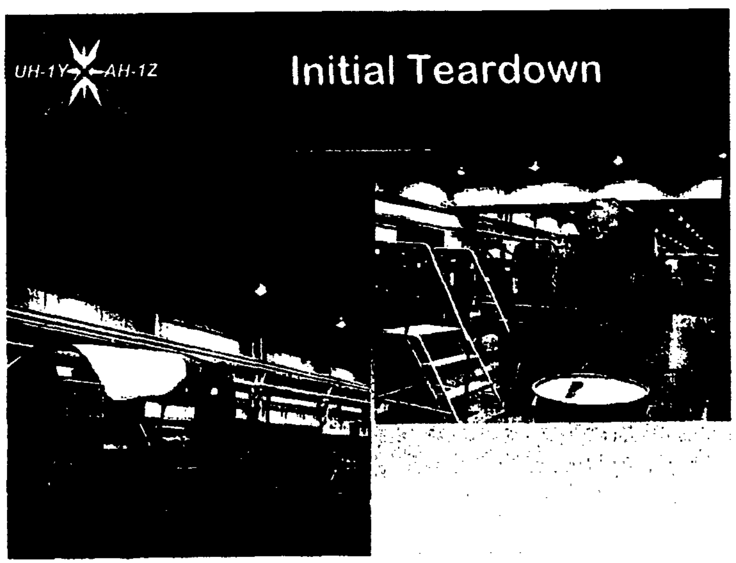
UH-1Y / AH-1Z

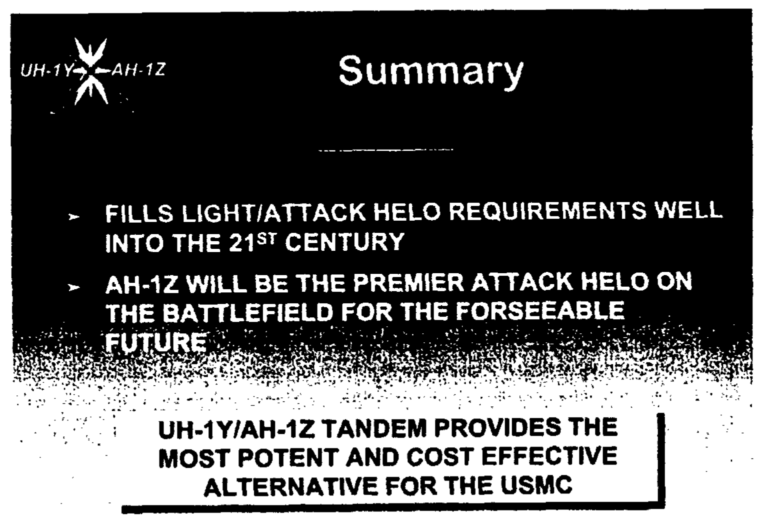


UH-1Y/AH-1Z SIGNIFICANTLY REDUCES LOGISTIC SUPPORT

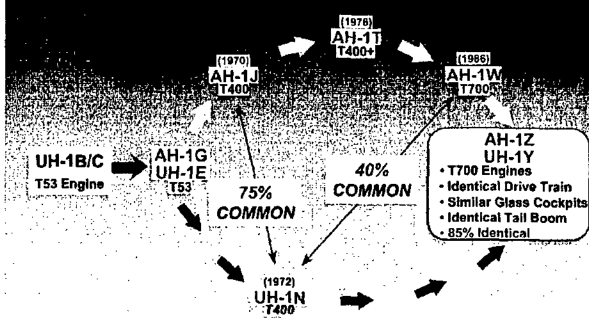

UH-1Y AH-1Z
'Snapshot' of H-1 Upgrade Support Equipment
1400
1200
1000
800
600
Total
Common
Total H-1 Upgrade SE Items 630
-Almost a 50% Reduction
(Current Total = 1223 Items)
Common Between AH-1Z/UH-1Y: 479
Total O-Level Items Identified: 268
- 106 CSE
- 162 PSE


UH-1Y AH-1Z
H-1 UPGRADES SCHEDULE
FY1997 FY1998 FY1999 FY2000 FY2001 FY2002 FY2003 FY2004 FY2005 FY2006 FY2007
CONTRACT AWARD
AH-1Z
FAB/INSTALL
FLIGHT TEST
CDR
1ST FLIGHT
OP ASSESS
OPEVAL
IOC
UH-1Y
FAB/INSTALL
FLIGHT TEST
CDR
1ST FLIGHT
OP ASSESS
OPEVAL
IOC
LRIP 1
LRIP 2
AH-1Z Production 2 11 18 24 24 24
UH-1Y Production 3 6 8 12 12 12


UH-1Y AH-1Z
Initial Teardown


UH-1Y AH-1Z
Summary
FILLS LIGHT/ATTACK HELO REQUIREMENTS WELL INTO THE 21ST CENTURY
AH-1Z WILL BE THE PREMIER ATTACK HELO ON THE BATTLEFIELD FOR THE FORSEEABLE FUTURE
UH-1Y/AH-1Z TANDEM PROVIDES THE MOST POTENT AND COST EFFECTIVE ALTERNATIVE FOR THE USMC

UH-1Y AH-1Z — USMC HUEY / COBRA EVOLUTION



UH-1Y AH-1Z — AH-1Z Firepower & Mission Flexibility

- 4 UNIVERSAL STATIONS
  - Sidewinder – Sidearm
  - Hellfire – Rockets
  - Auxiliary Fuel Tanks
  - Growth Potential For Future Weapon Systems
- 2 WINGTIP STATIONS
  - Sidewinder – Sidearm
- 750 ROUNDS 20mm w/FIRE CONTROL
- 3RD GENERATION TARGET SIGHT SYSTEM

UH-1Y AH-1Z — Integrated Wiring System

UH-1Y AH-1Z — PMA-276 Points of Contact

Comm: 301-757-xxxx DSN: 757-xxxx
http://140.229.62.192/public/pma276.html

Program Manager x-5534	Capt. Tom Curtis CurtisJT@navair.navy.mi
Asst. PM for Logistics x-5518	LtCol. A. H. Richardson RichardsonAH@navair.navy.mil
Deputy PM for Upgrades	Maj. Lindy Kirkland

FROM AUTOMATION TO AUTONOMY
-TRENDS TOWARDS AUTONOMOUS COMBAT SYSTEMS-

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SUMMARY

The development, procurement and utilization of defense systems will in future be strongly influenced by affordability. A considerable potential for cost reduction is seen in the extended use of automation reaching as far as autonomous unmanned systems. Starting with conventional and intelligent automation issues, this paper will describe important enabling techniques and technologies as a prerequisite for the implementation of future autonomous systems with goal- and behavior-oriented features. Main emphasis is being placed on information technology with its computational and machine intelligence (CMI) techniques. The treatment of conceptional system approaches will be followed by design considerations and then a global methodology for the engineering of future autonomous systems will be dealt with. Critical experiments for technology evaluation and validation will be mentioned together with a brief description of the main focus in future research.

1 INTRODUCTION

Tactical systems are implemented as Integrated Mission Systems (IMS) such as e.g. air and space defense systems. Key elements of IMS are - among others - platforms with sensors and effectors, ground based components with communication, command and control etc.

In technology, evolutionary progress is generally determined by the interaction between the "Requirements Pull (RP)" and the "Technology Push (TP)" (Fig. 1).

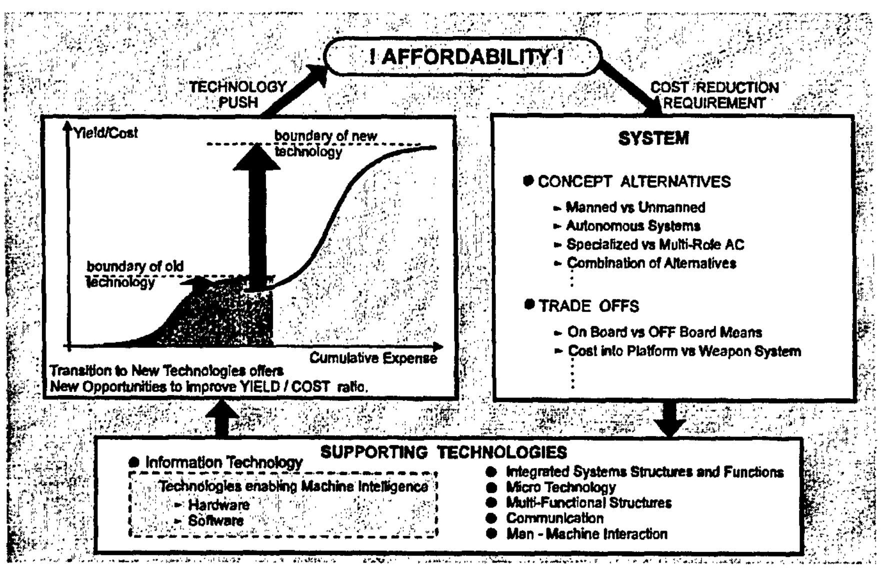


Figure 1: Requirements pull vs. technology push

Paper presented at the RTO SCI Symposium on "Advances in Vehicle Systems Concepts and Integration", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

Ever increasing requirements for more and more complex systems and their functions activate individual key technologies within the technological basis available or possibly to be created. However, new technologies - such as currently the new Information Technology (IT) - exert pressure towards increased requirements for new systems.

In the future progress primarily will be driven by economic aspects rather than by technological advances alone. Within this context "affordability" is of decisive importance. Advancing Technologies are essential for achieving unprecedented capabilities for new systems at affordable cost. Looking at Fig. 1 (upper left) the yield/cost ratio is plotted against the commulative expenses for old and new technologies (e.g. Information Technology). Considering the general performance potential, the transition to new technologies is mandatory to offer new opportunities and improved yield/cost ratios. Autonomous unmanned tactical systems surely are a viable step to cope with the cost reduction challenge and to improve cost effectiveness in the future.

2 INTELLIGENT AUTOMATION

Taking airvehicle as an example, the Unmanned (Uninhabited) Tactical Aircraft (UTA) or the Unmanned Combat Airvehicle (UCAV) are concepts to integrate advanced technologies into a complete tactical airpower system in order to enable a general purpose high performance aircraft to perform a full range of tethal missions without the physical presence of a pilot in the aircraft.

Figure 2 depicts the multi-dimensional closed loop guidance and control blockdiagram of an UTA resp. UCAV with the remote pilot or - more general - the operator being integrated through a bidirectional data link. Progressing from inside out the inner stabilization and control loop of the vehicle represents the lowest level of the hierarchical control structure. The next higher level performs flight path control followed by the mission and vehicle trajectory control as well as the weapon control functions beeing the highest level of the functional blockdiagram.

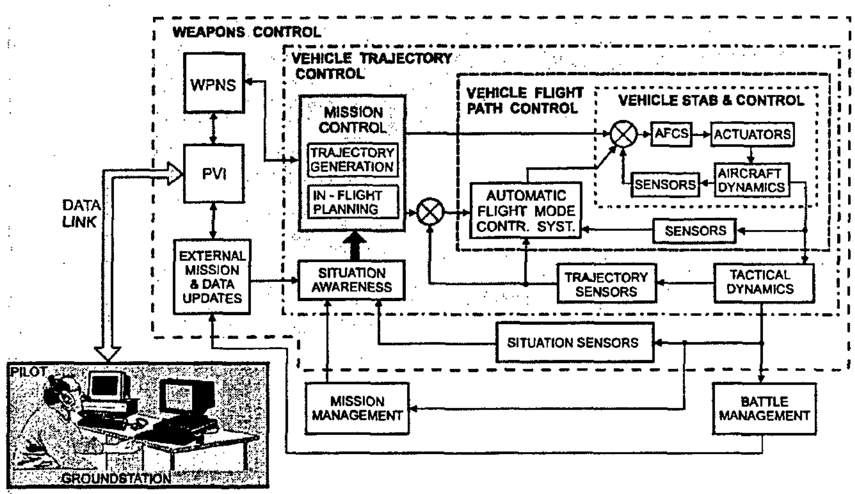


Figure 2: Cascaded airvehicle control loops

The key notions „automation" and „autonomy" are intimately connected with advances in Information Technology. Therefore emphasis is placed on this aspect.

Automation of most, if not all, of the said functions applying more or less conventional techniques such as algorithmic, numerical and expert system approaches coded in software for sequentiell processing, represents the state of the art concerning manned combat aircraft in use today.

As far as UTAs or UCAVs are concerned the obtainable level and performance of automation utilizing conventional techniques is not sufficient. Among others it would require too much of externed operstor's control intervention and hence pose very hard requirements for the data link.

To alleviate this problem, the objective and challenge is to replicate the operator's brain in the vehicle by artificial brain like information processing structures. For this purpose computational and machine intelligence (CMI) techniques as summarized in Figure 3 and dealt with in a little more detail under paragraph 3 and in [1] can be applied.

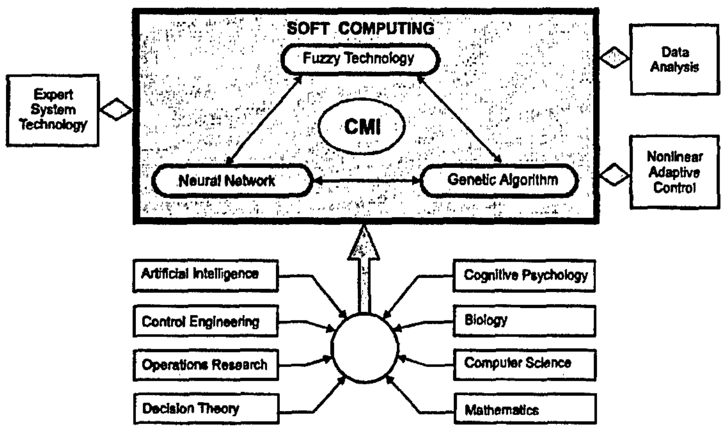


Figure 3: Soft-Computing/CMI and contributions from other areas

Often today they are aggregated under the notion of soft computing.

With that, technologies, techniques and methods are available, by means of which the cognitive abilities of humans for detection, classification, identification, assessment of a situation and of objects in it as well as for goal oriented behavior can attempted to be automated.

This is accomplished by designing and implementing corresponding artificially intelligent control elements, which roughly can be classified in to the different levels as indicated in Fig. 4.

These levels can be assigned to the functional levels of Fig. 2 accordingly. For further details it must be referred to the corresponding literature such as [3].

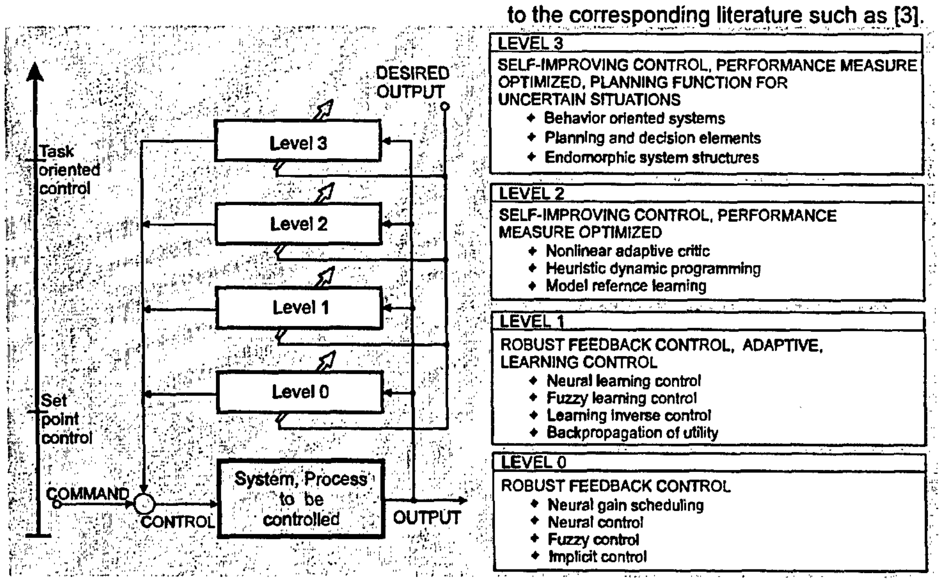


Figure 4: Levels of intelligent, knowledge-based control

Ever increasing complexity of systems is gradually leading to the limits of conventional and even intelligent control. In this context a complex dynamic system is characterized by the terms dimensionality, uncertainty and vagueness, interconnection of many subsystems as well as data and information explosion. To a large extent this applies to future unmanned tactical systems.

To cope with the said limits of control and automation of such systems, the transition to selforganizing autonomy must be performed and ways to design, built and operate autonomous systems must be established. The remainder of this paper is dealing with aspects of this challenge.

3 AUTONOMOUS SYSTEMS

Autonomy is the ability to function as an independent system, unit or element over an extended period of time, performing a variety of actions necessary to achieve predesignated objectives while responding to stimuli produced by integrally contained sensors. The following characteristics are therefore typical of an autonomous, behavior-oriented system:

- An "environment" (real world) is allocated to the system
- There is an interaction between the system and the environment via input and output information and possibly output actions
- The interactions of the system are concentrated on performing tasks within the environment according to a goal-directed behavior, with the system adapting to changes of the environment.

The interaction of the systems with the surrounding world can be decomposed into the following elements of a recognize-act-cycle (or stimulus-response-cycle).

- Recognize the actual state of the world and compare it with the desired state
(which corresponds to the goal of the interaction). (MONITORING)
- Analyse the deviations of actual and desired state. (DIAGNOSIS)
- Think about actions to modify the state of the world. (PLAN GENERATION)
- Decide the necessary actions to reach the desired state. (PLAN SELECTION)
- Take the necessary actions to change the state of the world. (PLAN EXECUTION)

To perform these functions, first of-all appropriate sensor and effector systems must be provided, as mentioned earlier. In the case of unmanned autonomous systems information processing means must be incorporated that apply machine intelligence to perform the tasks mentioned.

At this point and in this context the following question shall be addressed:

What is computational, machine or more generally artificial intelligence? In relation to the issues and topics treated here, the following answer shall be given.

- Systems/units have no artificial intelligence if a program/software „injects" them with what they have to do and how they have to react to certain pre-specified situations.
- Systems/units have artificial intelligence if their „creator" has given them a structure - not only a program - allowing them to organize themselves, to learn and to adapt themselves to changing situations.

Thus intelligent structures must be able to comprehend, learn and reason.

4 ENABLING NEW INFORMATION TECHNOLOGY

Paradigm shift to brainlike structures

The expected unprecedented advances in computing based on the conventional architecture, where processing is performed sequentially, do not yield the power for computational and machine intelligence.

There is a paradigmatic complementary shift from symbolic artificial intelligence techniques to a new paradigm, which is inspired by modelling the conscious and unconscious, cognitive and reflexive function of the biological brain.

Important related computing methodologies and technologies include inter alia fuzzy logic, neuro-computing and evolutionary and genetic algorithms as summarized in Fig. 5.

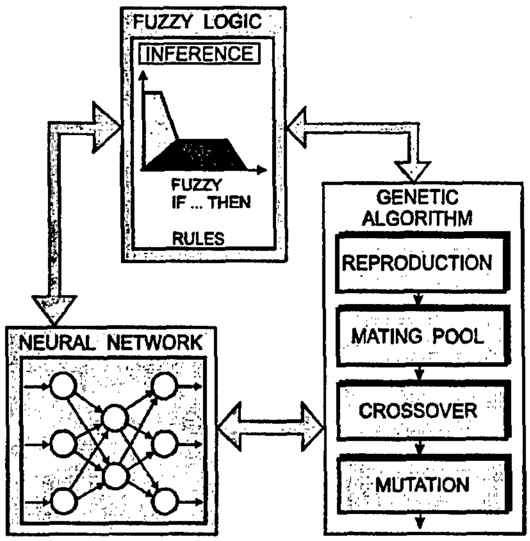


Figure 5: ***Biologically inspired computing technologies***

Fuzzy Logic

The theory of fuzzy logic provides a mathematical framework to capture the uncertainties associated with human cognitive processes, such as thinking and reasoning. Also, it provides a mathematical morphology to emulate certain perceptual and linguistic attributes associated with human cognition. Fuzzy logic provides an inference morphology that enables approximate human reasoning capabilities for knowledge-based systems. Fuzzy logic/fuzzy control has developed an exact mathematical theory for representing and processing fuzzy terms, data and facts which are relevant in our conscious thinking.

A unit based on fuzzy logic represents an associator that maps crisp spatial or spatiotemporal multi-variable inputs to corresponding associated crisp outputs. The knowledge which relates inputs and outputs is expressed as fuzzy if-then rules at the form IF A THEN B, where A and B are linguistic labels of fuzzy sets determined by appropriate membership functions.

Fuzzy rule based systems enable endomorphic real world modelling. With this technology human behavior can be emulated in particular as far as reasoning and decision making and control is concerned taking into account the pervasive imprecision of the real world. Fuzzy logic strongly supports realistic modelling and treatment of reality.

Artificial Neural Networks (ANN)

Neural Networks are derived from the idea of imitating brain cells in silicon and interconnecting them to form networks with self-organization capability and learnability. They are modeled on the structures of the unconscious mind.

Neurocomputing is a fundamentally new kind of information processing. In contrast to programmed computing, in the application of neural networks the solution is learnt by the network by mapping the mathematical functional relations. Neural networks are information processing structures composed of simple processor elements (PE) and networked with each other via unidirectional connections. The "knowledge" is contained in the variable interconnection weights. They are adjusted during a learning or training phase and continue to be adapted during operational use. With this capability the ANN represents an associator (like a fuzzy logic unit) that maps spatial or spatio-temporal multi-variable inputs to corresponding associated outputs. However, in contrast to a fuzzy-rule-based system the mapping function is learnt by the ANN. Neural Networks are capable of acquiring, encoding, representing, storing, processing and recalling knowledge. These are important prerequisites for endomorphic real world modelling.

Genetic and Evolutionary Algorithms

Genetic and evolutionary algorithms represent optimization and machine learning techniques, which initially were inspired by the processes of natural selection and evolutionary genetics.

To apply a genetic algorithm (GA) potential solutions are to be coded as strings on chromosomes. The GA is populated with not just one but a population of solutions, i.e. GA search from a population of points rather than from a single point. By repeated iterations a simulated evolution occurs and the population of solutions improves, until a satisfactory result is obtained. This is accomplished by iteratively applying the genetic operators reproduction, crossover and mutation.

Computer simulation is a viable tool to optimize behavior oriented systems by utilizing genetic or evolutionary techniques. Ever increasing processing speed enables the quick motion representation of events and processes, for which nature requires millions of years.

heavily on experience rather than on the ability of experts to describe the dynamic, uncertain world perfectly. This is accomplished by consideration of the tolerances for imprecision, uncertainty and partial truth to achieve tractable, robust and low cost solutions for complex problems.Thus, these techniques in conjunction with appropriate system architectures provide the basis for creating behavior-oriented autonomous systems.

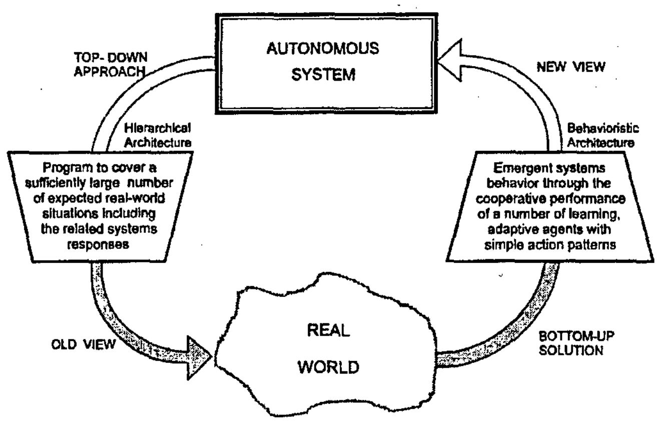


Figure 6: ***Top-down vs. bottom-up approach***

Conclusions

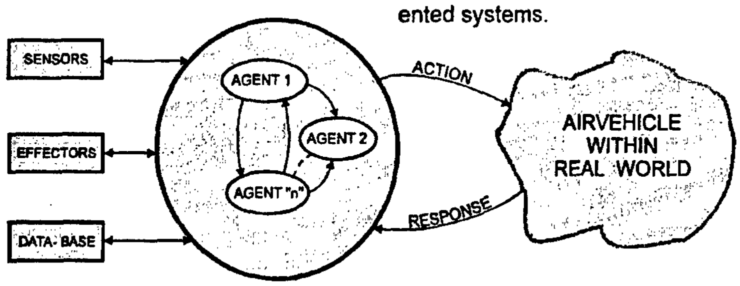
It was shown that fuzzy and artificial neural network techniques enable the endomorphic modelling of real world objects and scenarios. Together with conventional algorithmic processing, classical expert systems, probabilistic reasoning techniques and evolving chaos-theoretic approaches they enable the implementation of recognize-act cycle functions as mentioned. Genetic and evolutionary algorithms can be applied to generate and optimize appropriate structures and/or parameters to acquire, encode, represent, store, process and recall knowledge. This yields self-learning control structures for dynamical scenarios that evolve, learn from experience and improve automatically in uncertain environment. Ideally, they can be mechanized by a synergetic complementary integration of fuzzy, neuro and genetic techniques. These techniques support the move towards adaptive knowledge based systems which rely

5 CONCEPTUAL IDEAS

System architectures

The viable architecture must represent the organization of the systems intelligence and capability to behave, to learn, to adapt and to reconfigure in reaction to new situations in order to perform in accordance with its functionalities. Based on fundamentally different philosophies regarding the organisation of intelligence, two different architectures can be basically considered (Fig. 6). With the well known top-down approach as prevalently used to date a hierarchically functional architecture results. It structures the system in a series of levels or layers following the concept of increasing precision with decreasing intelligence when going from top to bottom. Implementation is characterized by the fact that for as many contingencies as possible the allocated system behavior is fixed in top-down programming. In fact, the real world is so complex, imprecise and unpredictable that the direct top-down programming of behavioral functions soon becomes very difficult if almost not impossible.

is depicted in Fig 7. The objective is to implement as many simple agents as possible with the associated behavior pattern, which then make the system act in a flexible, robust and goal-oriented manner in its environment through their additively complementary interaction. To enable the generation of emergent characteristics it must be ensured that the agents can influence each other mutually. Emergent functionality is one of the major fields of research dedicated to behavior-oriented systems.



AGENTS						
SENSOR DATA FUSION	PERCEPTION, SITUATION ASSESSMENT	PLANNING	....	PILOTING	THREAT	COMMUNICATION

***Figure 7:** System representation by agents*

Considerably different from the hierarchical structure is the subsumption architecture. It is based upon building functionality and complexity from a number of simple, parallel, elemental behaviors. It is sometimes called the behaviorist architecture and is based on a buttom-up approach. In this approach, so-called agents are implemented with the most simple action and behavior patterns possible so that the resulting emergent system behavior corresponds to the desired global objective. The system is able to adapt itself to changing situations in the environment by learning. The specific local intelligence of the individual agents generates a global intelligent behavior of the integrated overall system. Multiagent systems are complex and hard to specify in their behavior. Therefore there is the need to endow these systems with the ability to adapt and learn. This can be acomplished by the application of the technologies mentioned before.

A simplified block diagram of an autonomous system based on such a concept of cooperative AI/KB-Agents,

Intelligent hardware/software agents will fuse sensor information, monitor critical variables, generate optimized plans, alert operators through communication to problems as they arise and recommend optimized solutions in real time. Response agents capture basic data, communication (forecast and other information) and apply optimization technology to generate new plans based on changed conditions and states.

Design Considerations

Like in Engineering, it is also an indispensable prerequisite for an autonomous system that it is designed, constructed and trained according to a strict methodical approach. Fig. 8 shows such an approach in a very simplified form from today's technological point of view [4].

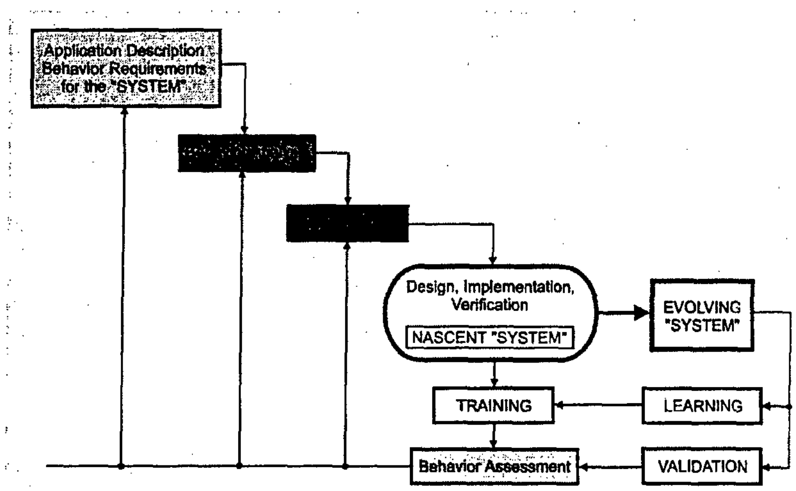


Figure 8: ***Engineering of the autonomous system***

It starts with the description of the physical system, its application, the initial environment, and the behavior requirements, with the latter being usually informally stated in natural language. The following behavior analysis is one of the major tasks. This step involves the decomposition of the target behavior in simple behavioral components and their interaction. Part of the specification is the architecture of the intelligent control system. It is the second key point during the engineering process. With the specification all information is available to design, implement and verify a nascent system, which is endowed with all its hardware and software components, however, prior to any training.

Based on a suitable training strategy the system acquires its knowledge during a training phase which is mandatory and prerequisite for appropriate behavior of the system. Training can usually be speeded up applying simulation including virtual reality. Within this context environments can be used that are much more changeable than the real ones.

After completion of training the behavior is assessed with respect to correctness (target behavior), robustness (target behavior vis-à-vis changing environment) and adaptiveness. Based on this assessment, further iterations during the engineering steps might become necessary in order to make the satisfactorily behaving system evolve from them in a step by step sense.

Implementation issues

Implementation issues like

- hardware for computational and machine intelligence
- software technology, software generation techniques
- autonomous control technology
- autonomous planning and routing
- integrated system structures and functions
- adaptive autonomy management

could not be treated here. It is referred to the Literature, e.g. [5].

6 EMERGENCE OF AUTONOMOUS SYSTEMS

The critical technologies, such as the new paradigm information and control technologies are indeed highly developed activities, however still mainly in universities and industry R.a.D. branches. Thus a time interval of 10 to 20 years is likely to elapse, until applications can be expected within systems as treated here.

Beyond the enabling technologies further technical issues such as

- maturity assessment
- system concepts
- critical experiments
- validation, certification techniques
- future research focus

shall be emphasized, because they critically influence the emergence of autonomous systems. Stepping back to the first chapter and recalling the interdependence of the Requirements Pull and the Technology Push it is of paramount importance for research planners to identify applications and requirements indicating the indispensable need for such systems and their capabilities. In this context the Uninhabited Tactical Aircraft (UTA) concept of variable autonomy currently under investigation, offers an ideal platform to perform critical experiments for the evaluation, validation and possibly certification of techniques and technologies.

Autonomous unmanned systems will be designed such that they offer fully autonomous operation. However, provisions will be incorporated allowing a human to monitor the system's operation and to intervene if required.

7 FINAL REMARKS

Complexity is a central problem in advanced system theory and engineering. The concept of building a high performance system around a central computer with top-down programming has long become obsolete. Well organized complexity with distributed CMI as briefly treated here is the way of the future.

Significant changes are currently taking place in the new information technology (IT) and other technological areas as far as functional capabilities, performance, characteristics and cost are concerned. These changes will support the new way and influence the users of related technologies and the supporting industries as well as their technical and organisational structures. Organizational structures have always reflected system structures. The rate of change and related realizations will exceed normal evolution and will have great social impacts accompanying the technological and functional advances. Instead of spin-offs considerable spin-in effects from commercial research and industry will impact military applications. Simultaneously a global availability of commercial High-Tech must be assumed.

In order to accommodate all this, the strategies of users and industry must be adapted accordingly. Looking at the interdependence of requirements, technologies, procurement processes and time behavior, 10 years is a short period.

WE MUST BEGIN NOW!

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SYMPOSIUM (A)

Aircraft Update Programmes.

The Economical Alternative?

TECHNICAL EVALUATION REPORT:

AIRCRAFT UPDATE PROGRAMMES. THE ECONOMICAL ALTERNATIVE?

By

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INTRODUCTION

This SCI Symposium on Aircraft Update Programmes asked a very important and timely question, "Are Update Programmes the Economical Alternative?" The alternative , of course, being a new system development program (such as the Eurofighter or F-22) or replacement program (such as buying new F-16s or C-130s). The reason that this topic is so important and timely is that all NATO members are facing (1) decreasing military budgets, (2) increasing diversity of the threat and (3) all systems are ageing and becoming obsolete. Even though the USSR has become dismembered and no longer poses a single global threat, the regional conflicts and terrorists activities poses a more demanding diverse threat The NATO members are expected to meet this diverse threat with ageing systems and decreasing military budgets.

The symposium was broken into five sessions:

1. Overview and Lessons Learned (Part I)
2. Cockpit
3. Sensors
4. Engine
5. Overview and Lessons Learned (Part II)

The options for the NATO members are the development of a new system, replacement with a new off-the-shelf (OTS) system or the upgrade of the existing system. The upgrade of the existing system can be in the form of:

1. Structural life extension program (SLEP)
2. New engines
3. New avionics
4. New weapons

The symposium addressed the first three but ignored the very important consideration of new weapons. A new weapon can breathe new life into an otherwise obsolete platform. For example, the stand-off cruise missiles currently in development (US JASSM, UK Storm Shadow and the German Taurus) will provide hard target kills without the launch aircraft having to penetrate a heavily defended area.

The decision to pursue a new system development, replace with a new system or upgrade an existing system must consider several factors. One very important consideration is that the development of a new system will cost (non-recurring plus recurring) at least ten times the cost of an upgrade program. Even the recurring cost of replacement with a new OTS system will be more (typically a factor of five) than the upgrade of an existing system since the existing system is a sunk cost. A NATO member must do a very careful and thorough cost-benefit study before embarking on a new system development program as the risk is high and the cost is great. A critical part of the cost-benefit study is to establish what has rendered the current system obsolete. Is the obsolescence due to (1) new applications, mission or requirements, (2) changing threat, (3) system becoming too expensive to operate, or (4) is the current system just worn out? If the decision of the cost-benefit analysis is to upgrade the existing system there needs to be 10-15 years of airframe life remaining after the the upgrade.

The current situation in NATO is that there are a few new system replacement programs, fewer still new system development programs but many upgrade programs. The symposium audience heard from many of the upgrade programs.

OVERVIEW AND LESSONS LEARNED

Paper #1 by Andrew Kerr (NASA Ames Research Center, Moffett Field, Ca) offered some interesting perspectives on rotorcraft technologies. He pointed out that the technologies for rotorcraft are different than for fixed wing aircraft due to the unsteady and unsymmetrical loadings. He offered a process for deciding between a new system versus an upgrade program, and emphasized that the principle parameter will be cost. The trend for helicopters is that the engine will be upgraded at least once during the aircrafts lifetime. The technology community is making great strides in structures/materials with the potential for significantly improved rotorcraft systems.

Mr. G. LeBretton (Thomson-CSF, France) made an interesting observation on upgrading fighter aircraft in **Paper #7**. Mr LeBretton observed that the following fighter operational needs, can all be met with upgrades to existing fighters:

1. Improved range
2. Multirole capability
3. Decreased attrition (improved survivability)
4. Decreased collateral damage (improved accuracy)
5. Day/night and all weather operation
6. No friendly kills (improved IFF)

Thus, why pay 4 to 5 times more for a new aircraft replacement when the existing fighter fleet can be retrofitted to meet the needs. The author hastens to point out that the fighter upgrade will serve for an additional 12 to 15 years and not the 30 years of a new fighter. This observation is endorsed by the electronics manufacturers who have made avionics upgrades a profitable line-of-business. However, this observation is not in the best interest of the aircraft manufacturers who spend considerable budget to convince their military that the right answer is a new fighter aircraft development.

Paper #13 by E.C. Vaught and L.B. Giles (Bell Helicopter Textron, Ft. Worth, Tx) discussed a systems engineering process for developing a strategy for long-term systems and technology advancement. The paper argued that ground based systems integration solutions must supplant aircraft testing to the maximum extent possible in order to accommodate rapid and economical test results without expending valuable aircraft time. In addition, training for pilots, crews, and maintainers must move to improved ground training systems, such as full flight simulation trainers and non-motion cockpit trainers.

The integration of defensive aids was the topic of **Paper #14** by Dr. Philip Zanker (DERA, Farnborough, UK). He presented a three layered approach to survivability: (1) threat avoidance – route around threats to avoid detection, (2) minimize danger by confusing or suppressing the enemy, and (3) close-in defense by immediate threat warning and terminal countermeasures. The key to self protection is situational awareness. There are four levels integration for the defensive aids:

1. Basic mechanical and electrical – the integration of separate subsystems, each complete with its own set of displays and controls. (least expensive)
2. Integrated Defensive aids suite (IDAS) – integrated within itself with a common means of display and control.
3. IDAS with avionics integration – integration into existing cockpit displays and controls, and weapons and databases

4. DAS within a federated or integrated modular avionic architecture – the defensive aids become an intimate part of the flight avionics suite. (most expensive)

The customer specification will drive the desired level of integration but cost will determine the achieved level.

Paper #15 by Christian Dedieu-Eric Loffler (SAGEM SA) presented an already fielded implementation of an avionics upgrade package developed to offer a modular solution to a wide range of modern operational requirements. The SAGEM SA upgrade concept allows one to match specifications ranging from basics performance enhancement, such as high accuracy navigation for low level flight, up to full multi-role capability with sophisticated air-to-surface weapon delivery and multi-target air-to-air fire control.

UPGRADE PROGRAMS

UH-1/AH-1 Upgrade to the UH-1Y/AH-1Z For the USN/USMC

Three papers from the US addressed the upgrade programs for the USN/USMC UH-1 Huey and AH-1 Cobra helicopters. The **Keynote Address** by Capt J.T. Curtis USN (Program executive Office, AIR ASW Assault & Special Mission Program), **Paper #2** by Alan W. Myers (Technical Director, H-1 Upgrade, Bell Helicopter Textron) and Major Paul Davidovich UCMC (Class Desk, H-1 Upgrade), and **Paper #12** by J.A. Dowell (Litton Guidance and Control systems) discussed the structural, propulsion and avionics upgrades to 180 AH-1 and 100 UH-1 helicopters.

Capt. Curtis pointed out that the USN and USMC plan to reduce their VTOL fleet to the CH-53E, V-22 and the AH-1Z/UH-1Y over the period 2000-2020. Currently the Huey and Cobra are about 20 percent common. The goal of the upgrade program is to increase the commonality to 85 percent. The upgrade program will triple the radius of the AH-1Z with 8 Hellfire missiles. The UH-1Y radius will increase to 133 nm from almost zero for the UH-1 with 8 troops, 4 aircrew and 30 minutes time-on-station.

The improvements to the Cobra helicopter include a new tailrotor and gearbox, electrical system, weapons pylons, hydraulic system, landing gear, crashworthy crew seats, main rotor and transmission, integrated glass cockpit and targeting sight system. In addition, the Cobra has received new GE-T700-401 engines and IR suppressor, airframe mods to provide for increased weight, more survivability and a 10,000 hour fatigue life, an APU and increased fuel capacity for more range. Similarly the Huey has received most of the Cobra improvements plus a 21 inch fuselage stretch into new primary structure. The contract award for the H-1 Upgrade Program was in early FY 1996 and the schedule shows low rate initial production in 2002 for the AH-1Z and 2003 for the UH-1Y.

Helicopter Modernization With Advanced Engines

Paper #18 by Fred Dickens (Rolls-Royce Allison, Indianapolis, In USA) discusses the modernization of current helicopters with engine upgrades. He discusses the re-engine programs for the CH-47 Chinook, OH-58 Kiowa, UH-60 Blackhawk, AH-64 Apache, and Westland Lynx, but spends most of the paper on the US Army UH-1H. The US Army's UH-1H was a good candidate for an engine upgrade since it had substantial airframe life out to 2025. Replacing the T 53 engine in the UH-1H with the T 800 (developed for the US Army RAH-66 Comanche) improves the mission endurance by 50 percent and the range or payload by 58 or 47 percent respectively. Because of the improved RM&S of the T 800 engine, an operator will be able to recover the cost of the re-engining through the savings realized from as few as two T 53 overhauls. The paper also discusses the factors involved in deciding between replacement or upgrade. Replacements are appropriate when the mission need and capability of the replacement is so compelling that upgrades to the existing system are simply cost prohibitive. A decision to extend the life of a system with an upgrade program is appropriate when the mission has remained relatively unchanged and technology is available to directly enhance mission effectiveness.

F-16 A/B Mid-Life Update (MLU) Program

Paper #3 by V.L. Denena (Lockheed Martin Tactical Aircraft Systems Co., Ft. Worth, Texas) addressed the cockpit and avionics upgrade of 360 F-16 A/Bs in the US, Belgium, Norway, Netherlands and Denmark. This MLU Update Program involved a kit development and in-country production effort currently extending from 1990 through 2003. The kits are for block 1/5/10/15 aircraft but could be adapted for block 25/30/40 aircraft. The cockpit upgrades include a WAC HUD, up-front controls, two CMFDs, side-stick throttle, NVG compatible, night operations capable and CCTVS/CAVTR. The avionics upgrades are a digital terrain system, GPS, electronic warfare management system, advanced IFF, APG-66(V)2 radar, improved data modem, modular mission computer and inlet hard points for a FLIR pod or target pod. The depot modification requires complete depaneling of aircraft and teardown of crew station and avionics equipment bays. Approximately six months and 2500-4000 manhours (depending on block number) are required to perform the work. The modification work is well underway and on schedule with approximately 75 aircraft modified to date. The cost/benefit study conducted in the late 1980s concluded that the MLU program cost was substantially less than a new aircraft.

The Tornado IDS Mid-Life Upgrade Programmes

Paper #4 by T. Watkins (British Aerospace) and **Paper #6** by D. Hoffman (Daimler-Benz Aerospace, DASA) addressed the upgrade of the Tornado (Interdicter Strike) with modern avionics. One hundred and forty two British GR-1s are being reconfigured into the GR-4 with the introduction of the following new avionics equipment:

1. New sensors and displays consisting of a FLIR, multi-function displays with digital map, wide-angle HUD, computer symbol generator, video recording system and a computer loading system
2. New armament control system consisting of a stores management system, a weapon interface unit linked to a 1553 databus within a 1760 interface
3. Night vision goggle compatible cockpit
4. Terrain reference navigation/terrain following display/terrain following switching and logic unit/covert radar altimeter

The development work was completed in1998 with production mods scheduled through 2003.

The German Tornado MLU is a two phase program. Phase I scheduled for the year 2000 includes:

1. Enhanced main computer with a new Ada software (ASSTA) and a digital weapon bus
2. Integration of GPS and a laser INS into the navigation system
3. Integration of the GBU 22 and 24 LGBs and the Harm III

Phase II, scheduled for 2004, includes:

1. Integration of colored LCD displays, a digital map, and new EW warning indicators
2. Integration of the new stand-off cruise missile Taurus
3. Integration of an improved radar warning receiver
4. Integration of an enhanced Tornado nose radar
5. Provision for a radar reconnaissance pod

Mirage 2000 Mid-Life Upgrade Programme

Paper #5 by Alain Picard and Laurent Madon (Dassault Aviation) presented the MLU program for the Mirage 2000. The aircraft airframe life is estimated to last through 2020, thus an avionics upgrade offered a cost effective modernization plan. The MLU program will comply with the following criteria:

1. Replace current sensors with state-of-the-art modern sensors with up to date operational performance
2. Replace the current WNDS core system with an open system based on modular avionics architecture allowing, in particular, to separate application software and hardware.

3. Replace the current cockpit with a modern glass cockpit taking benefit of the numerous advantages of the man-machine interface fitted on the Mirage 2000-5.

The target of this mid-life update is to obtain a more modern Mirage 2000 at 80 percent of the cost of a Mirage 2000-5.

Aircraft Life Extension – CC-130 Hercules Avionics Update

Paper #10 by Major Chris Daley (Canadian National Defence Headquarters, Ottawa, Canada) presented the avionics update program for their Hercules transports. The Canadian CC-130 transports had their structural life extended beyond 2010 by earlier SLEP programs, so that an avionics upgrade was a very cost-effective solution for modernization. The CC-130 fleet of 32 aircraft is composed of six different Hercules models, each equipped with a different avionics configuration. It was estimated that the avionics systems would become unsupportable or obsolete by 2010. It was considered essential from an operational and economic standpoint that all aircraft receive a standard and updated avionics suite. The paper presented an excellent discussion of the process and results of the Canadian Department of National Defence cost-benefit analysis. The 32 aircraft have been modified for about $40M (Canadian) in non-recurring and $3M per aircraft.

Cockpit Upgrade For the G222 to C-27J

Paper #11 by Gianluca Evangelisti and Maurizio Spinoni (Alenia Aerospace) described the cockpit modification to the Italian G222 tactical transport to develop the C-27J. The C-27A was a joint development by Alenia and Lockheed Martin building on the rugged G222 design and incorporating new avionics, propulsion and general subsystems. The cockpit upgrades, developed for the C-130J, were incorporated into the C-27A to produce the C-27J. The paper presents a description of the main cockpit features and the process used to select a cockpit configuration that allows optimized operational capabilities while reducing overall development costs.

MH-53J Service Life Extension Program

Paper #23 by Charles Crawford (Georgia Tech Research Institute) and Col. Henry Mason (USAF, Director of SOF System Program Office, Warner Robins AFB, Ga) presented a summary of the air vehicle modifications (largely structural) that were made and the airworthiness qualification flight test program that was conducted to increase the operational gross weight and enhance the structural integrity of the CH-53J. The impact on both vibration and dynamic component retirement times are discussed. The paper includes both technical and cost information to support the cost- benefit analysis for the modernization program. The SLEP was completed in 1990 and increased the helicopters life past 2000 towards the V-22 IOC. The program non-recurring cost was approximately $40M (US) with a unit recurring cost of $2.4M for 41 aircraft.

Canadian CF-188 and CP-140 Service Life Extension Programs

Major Normand Landry (Canadian National Defence Headquarters, Ottawa, Canada) presented a very nice analysis for the selection of SLEP for their CF-188 and CP-140 fleets in **Paper #24.** Canada has decided to perform a structural and systems upgrade on their CF-188 and CP-140 aircraft. These upgrades will allow the aircraft to meet their operational requirements until the first quarter of the next century. The choice for this course of action was based upon option analysis studies. This paper presents the approach taken and the assumptions made for the various option packages studied to reach that conclusion. Avionics packages are readily available OTS and in most cases the decision is based mostly on structural limitations.

Transall C-160 Life extension and Avionics Upgrade Programs

Paper #26 by P. Blumschein (Daimler Chrysler Aerospace) discussed the structural life extension and avionics upgrade programs for the German Transall C-160 transport. Starting in 1984, the C-160 has undergone several structural life extension programs: (1) cold working in the wing area, (2) reinforcement of the wing area, and (3) prevention and corrective measures on the entire airframe. These efforts have extended the airframe life of the aircraft from the original estimate of 1990 to at least 2010. Starting in 1987 an avionics upgrade program has been ongoing continuously to the present. This program has replaced obsolete and hard to support equipment with more modern avionics. A self defense system was installed from 1992 to 1999 consisting of radar warning, chaff/flare dispenser, missile approach warning system and an electronic warfare management system. According to the present planning, the C-160 will be in service to 2018. Since the aircraft first entered service in 1967, this is an average service life of more than 50 years. For this aircraft the cost of the upgrade programs is less than 20 percent of a new aircraft purchase. Thus, the upgrade programs are indeed a cost-effective alternative for the Transall C-160.

USAF Bomber Upgrade Program

During the panel discussion, information about the USAF bomber road map was presented. The USAF has concluded that they will need a new long range, large payload, rapid response bomber by 2037. This means that the 76 B-52s, 93 B-1s and 21 B-2s will need to provide the bomber fleet mission until that date. It should be noted that the year 2037 would mean approximately 80 years of service for the B-52. The aircraft, for the most part, have the airframe life to extend to 2037. However, the USAF will embark on a three phase upgrade program, mostly modern avionics, displays and defensive aids. The USAF has programmed $2.3B (US) for a three phase upgrade plan:

1. $923M in 2000 to 2010
2. $678 M in 2006 to 2015
3. $685M in 2015 to 2025

All three aircraft will be given precision, stand-off capability with the integration of the US JSOW and JASSM weapons. A new bomber development program would be initiated no later than 2013.

SUMMARY AND OBSERVATIONS

With regard to the original symposium question, "Are aircraft update programmes the economical alternative?", the answer is a resounding YES. With a new aircraft development program costing at least a factor of 10 more than an upgrade program, it is difficult to make a case for a new aircraft development. Oft time the new aircraft program is driven by national pride and pressure from the prime aerospace companies, rather than the evidence from an honest and thorough cost-benefit study. Even replacing the existing aircraft with new off-the-shelf aircraft will cost a factor of 5 or more than upgrading the existing aircraft. The shortcoming with upgrading an existing aircraft is that its useful life is extended another perhaps 20 years at most, whereas a new aircraft would give double the life.

The symposium did not address upgrading an existing aircraft with a new weapon. This important upgrade option would make a good follow-on symposium.

Several of the papers were pure sales pitches for supplier products. Symposia such as this one are not the forums for marketing presentations.

THE H–1 UPGRADE PROGRAM: AFFORDABLE WAR FIGHTING CAPABILITY FOR THE U.S. MARINES

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ABSTRACT

In late 1996, Bell Helicopter Textron Inc. was awarded a contract from the United States Marine Corps for the H–1 Upgrade Program. The program award was preceded by studies of all aircraft and approaches available to provide helicopter war fighting capability for the Marine Air Ground Task Force through the first quarter of the 21st century and beyond. Upgrades were defined for both the UH–1N utility helicopter and the AH–1W attack helicopter to integrate the following enhancements:

- Improved mission capability
- Increased performance and maneuverability
- Additional survivability features
- Reduced pilot workload
- Potential for growth

These enhancements give the Marine Corps the equivalent of new, state-of-the-art, zero-time aircraft, with 10,000-hour service lives.

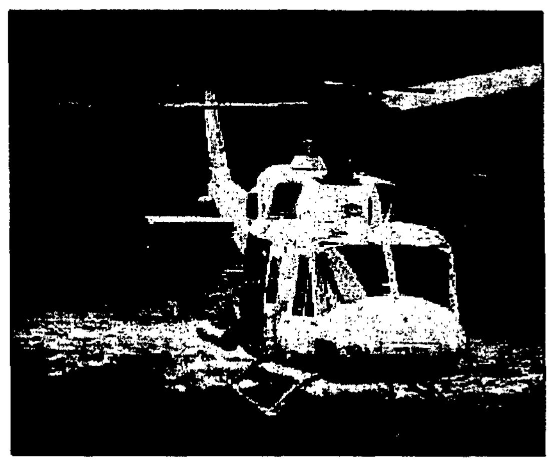
Total ownership cost affordability was, of course, a major requirement. Commonality, improvements in reliability and maintainability, the use of COTS/NDI equipment, and the reuse of existing equipment were encouraged to enhance squadron operability and supportability and help reduce recurring and O&S costs. Cost As An Independent Variable (CAIV) studies were also required to continuously evaluate potential cost reduction elements in trade against program and technical requirements.

Bell and NAVAIR formed Integrated Product Teams (IPT) with representatives from all functional disciplines, to improve communication and to ensure the configuration designs were not only adequate technically but were also cost-effective to manufacture and to operate and support in the fleet. This IPT process has been instrumental in improving the contractor/customer approval process during design reviews.

This paper summarizes the H–1 Upgrade Program. The Marine Corps modernization plan is described and the role of the H–1 is defined. The resulting configurations are described, as is the process of optimizing configuration details within program constraints.

INTRODUCTION

The current U.S. Marine Corps (USMC) utility helicopter, the UH–1N Huey, was fielded initially in 1970. The versatile Huey has been modified over the years with added systems that have increased its roles and mission utility, as summarized in Fig. 1. These modifications have also resulted in weight increases that have adversely impacted its payload and power-available



UH–1N "HUEY"
Airframe: Bell Helicopter
Engines: T400-PW-400
105 Aircraft Inventory
Last Produced 1979

Mission Tasks

- Airborne command & control
- Combat assault support
- Control of supporting arms
- Special operations support
- Search & rescue augmentation
- Medical evacuation
- Shipboard & austere base ops
- Night & adverse weather ops
- Visual reconnaissance

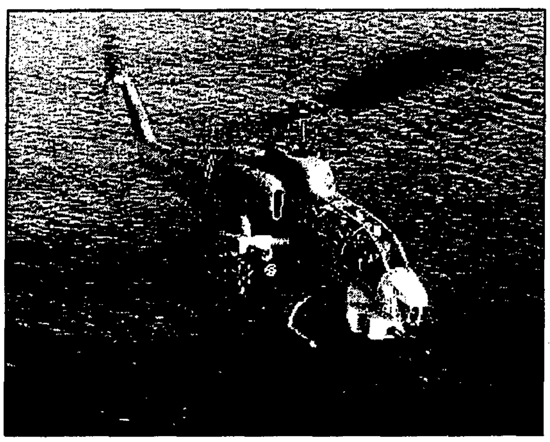
Fig. 1. Marine light helicopter today, the UH–1N

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

margin. Additionally, the fielded aircraft are approaching the end of their service life, and have become an increasing logistic and maintenance burden to the fleet.

The AH–1W Super Cobra, the current USMC attack helicopter, was initially fielded in 1986. The AH–1W is a modification of the AH–1T that incorporated the GE-T700-401 engines. Like the Huey, the Cobra has been upgraded incrementally with advanced avionics and weapons systems to maintain a viable capability against evolving threats. These sequential upgrades, without optimal integration, have come at the cost of increased aircrew workload that impacts mission effectiveness. Mission tasks are shown in Fig. 2.

The Marine Corps attack and utility helicopters are uniquely consolidated into the same squadron for training, maintenance, and deployment. Over the years, the divergence of the AH–1W and UH–1N configurations has resulted in increased support costs for maintenance,



AH–1W "SUPER COBRA"
Airframe: Bell Helicopter
Engines: T700-GE-401
201 Aircraft Inventory
Final Deliveries 1998

Mission Tasks

- Transport helo support
- Ground force fire support
- Control of supporting arms
- Search & rescue augmentation
- Visual & armed reconnaissance
- Shipboard & austere base ops
- Night & adverse weather ops
- Anti-armor operations
- Anti-helicopter operations
- Enemy fixed wing defense

Fig. 2. Marine attack helicopter today, the AH–1W.

training requirements, procurement of spares, support equipment, and publications. Therefore, the Marine Corps desired an upgrade approach that would increase commonality between the aircraft.

In addition to correcting existing deficiencies to the current aircraft, the Marine Corps recognized the need to modernize their attack and utility helicopters to meet emerging and future mission needs. These requirements include

- Operations at greater ranges and with larger payloads.
- Command, control, and communications interoperability.
- Expanded night and reduced visibility operations.
- Improved targeting sensors and weapons.
- Survivability enhancements.

A high degree of growth potential was desired that would allow efficient reaction to rapidly evolving future threats, technologies, and mission requirements.

This modernization would occur in a period of austere budgets driven by simultaneous modernization of multiple major weapon systems. A series of trade studies were conducted to determine the most cost-effective way to provide utility and attack helicopter warfighting capability for the Marine Air Ground Task Force through the first quarter of the 21st Century. In late 1996, as a result of these trade studies, Bell Helicopter was awarded a contract for the H–1 Upgrade Program, which will remanufacture the AH–1W and UH–1N into the AH–1Z and UH–1Y. The Upgrade Program is a part of the Marine's "neckdown plan" for VTOL aircraft, as shown in Fig. 3. This paper describes the H–1 Program with emphasis on the team approach and metrics, the resulting configurations, and the improved mission effectiveness of the aircraft.

REQUIREMENTS

To ensure that the design of the aircraft addressed current operational shortfalls, the team of government and contractor personnel reviewed all identified deficiencies from past developmental and operational testing and from 20 years of fleet experience. In addition, to maximize reliability and maintainability in the new design, the team analyzed major maintenance and logistic cost drivers. The analyses included reviewing current mission readiness degraders, maintenance man-hour drivers, and logistic action chits. Site interviews were also conducted at all levels of maintenance—organizational

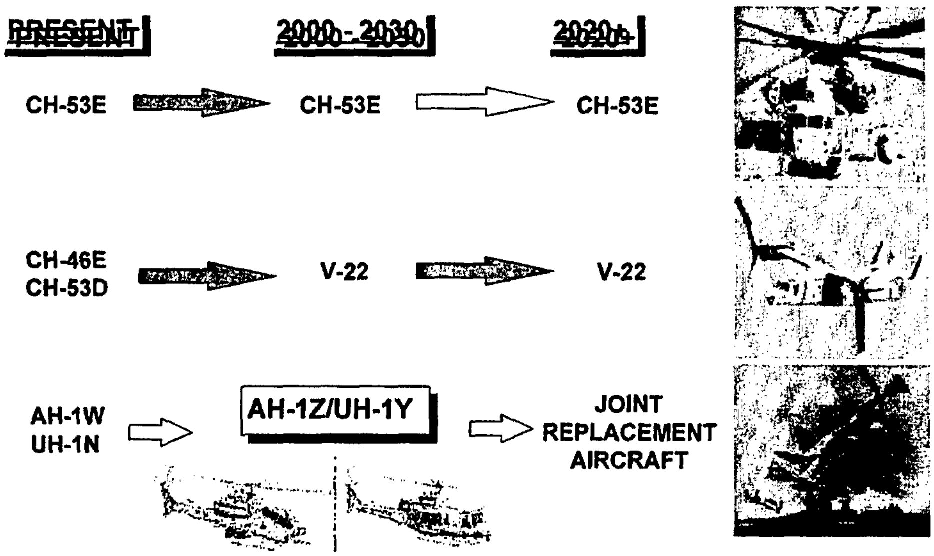


Fig. 3. The USMC VTOL neckdown plan.

through depot—to identify other unreported areas of concern.

Total ownership cost affordability was, of course, a major design driver. Maximum commonality between the aircraft and other DOD assets, combined with improvements in reliability and maintainability, were required to reduce recurring costs, qualification and flyaway costs, and all operating and support costs. Commonality was not limited solely to the aircraft components, but also included spares, maintenance, training, support equipment, and publications. The use of commercial off-the-shelf/nondevelopmental items (COTS/NDI) equipment and reuse of existing equipment were also encouraged, to reduce costs.

In addition to the more obvious operational capability enhancements, the design teams had to be cognizant of the other factors that make the aircraft deployable "in every clime and place." Design specifications were provided that defined the Marine shipboard and ground operating environments, namely:

- Material and manufacturing techniques to resist the harsh and corrosive environment.
- Hardening of avionics and electrical distribution systems to operate in the electromagnetic environment.
- Additional structure to react high sink-rate landings.
- Tiedowns for extreme winds and ship motions.
- Minimum space required for aircraft, support equipment, and spares stowage.
- Extreme operating temperature range from –65°F through +125°F.
- Survivable occupied space when subjected to accelerations of 20*g* longitudinal, 20*g* vertical or 10*g* lateral.
- Crash-attenuating crew and troop seating.
- Redundant load paths, with damage and flaw tolerant structural design criteria to ensure safe operations.
- Extension of dynamic component lives to 10,000 flight hours, and gearboxes with a design objective of 5,000 hours between overhauls.

In addition, the Marines required heavy emphasis on design concepts to minimize intermediate level maintenance with a desire for either unit level (O) or original equipment manufacturer (OEM) repairs.

With these requirements, the Bell/NAVAIR/Marine Corps teams began the design process.

THE DESIGN PROCESS

Bell, the Naval Air Systems Command (NAVAIR), and the Marines recognized the advantages of working in Integrated Product Teams (IPT), and all entities had previous experience using such teams. Recent experience included the Bell/Boeing V–22 program. To manage the H–1 Upgrades program, an organization was defined (Fig. 4) using the Program's work breakdown structure elements (WBSE). A Core Team, with members from Engineering (the authors), Program

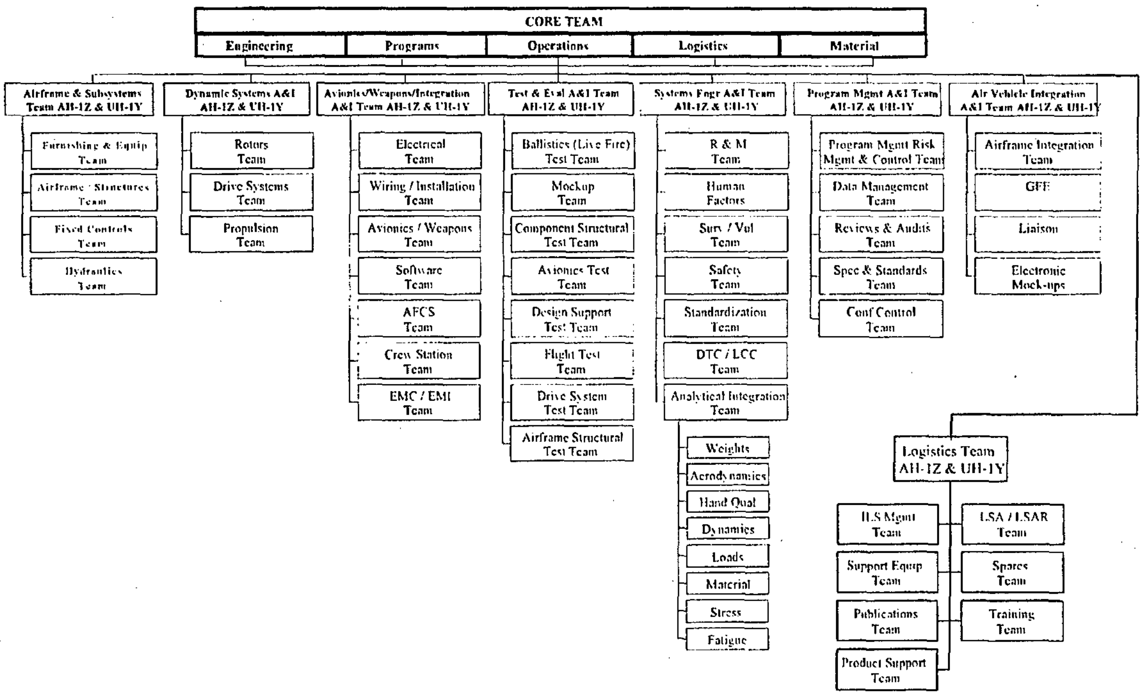


Fig. 4. H–1 upgrade program team organization.

Management, Operations (Tooling and Manufacturing), Materiel (including Procurement), and Logistics was given the responsibility to execute the Program within budget and Statement of Work constraints. Major subcontractors also participated on the Core Team.

The next level of management was the Analysis and Integration (A&I) Teams, which were responsible for several IPT elements and were organized in the same manner as the Core Team, with representatives from all functional disciplines.

The Integrated Product Teams were responsible for the discrete "Products" of the H–1 configurations. Although the accounting for the two helicopter configurations was kept separate for tracking purposes, the IPTs generally had responsibility for both aircraft (the Airframe IPT had both the AH–1Z and UH–1Y airframes, for example). Technical leaders from Bell, NAVAIR, and the Marine Corps were resident as IPT members with responsibilities initially for defining requirements and then for creating design concepts to satisfy these requirements. The Marine Corps had Resident Integrated Logistics Support Detachment (RILSD) members who brought fleet experience to the design process.

The IPT process is illustrated in Fig. 5, with many factors that had to be balanced to provide the optimum solution. The IPTs developed cost, weight, and reliability and maintainability goals to support program requirements; these goals, together with budget and schedule constraints, were used to help balance the design through trade studies.

The Marines encouraged the use of the Cost As An Independent Variable (CAIV) process during design trades and interactions, where the IPTs could address any variable—configuration or program—to keep costs down. Through Critical Design Review (CDR), nearly 250 of these studies had been conducted and 57 were incorporated, saving over $800,000 in aircraft recurring costs.

Technical Interchange Meetings (TIM) were used and found to be very beneficial in encouraging communication between all IPT members. These TIMs were held frequently, as shown in Fig. 6. The success of the process is summarized in Table 1, where the program technical status relative to targets is summarized at the time of the Preliminary Design Review (PDR) and at the CDR. The teams did an excellent job of meeting or exceeding targets and also made significant progress in most areas in the 14 months between PDR and CDR. The CDR was especially successful, with the Chairman, Mr. John McKeown, Naval Aviation Systems Command, commenting that "the CDR was an exceptionally fine one."

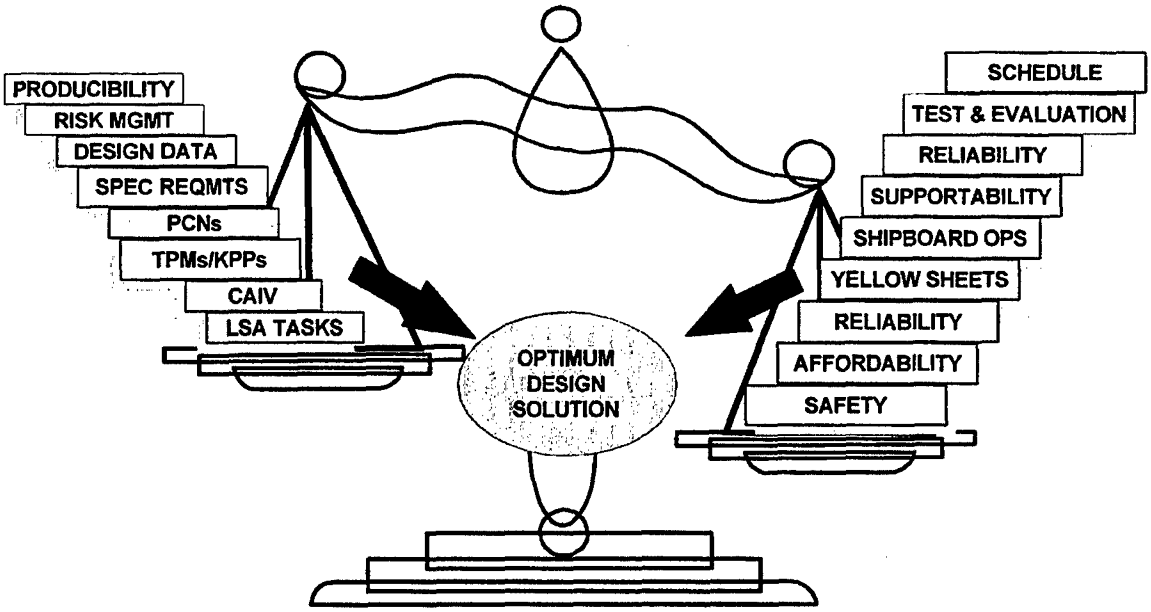


Fig.5. Balancing requirements to meet program needs.

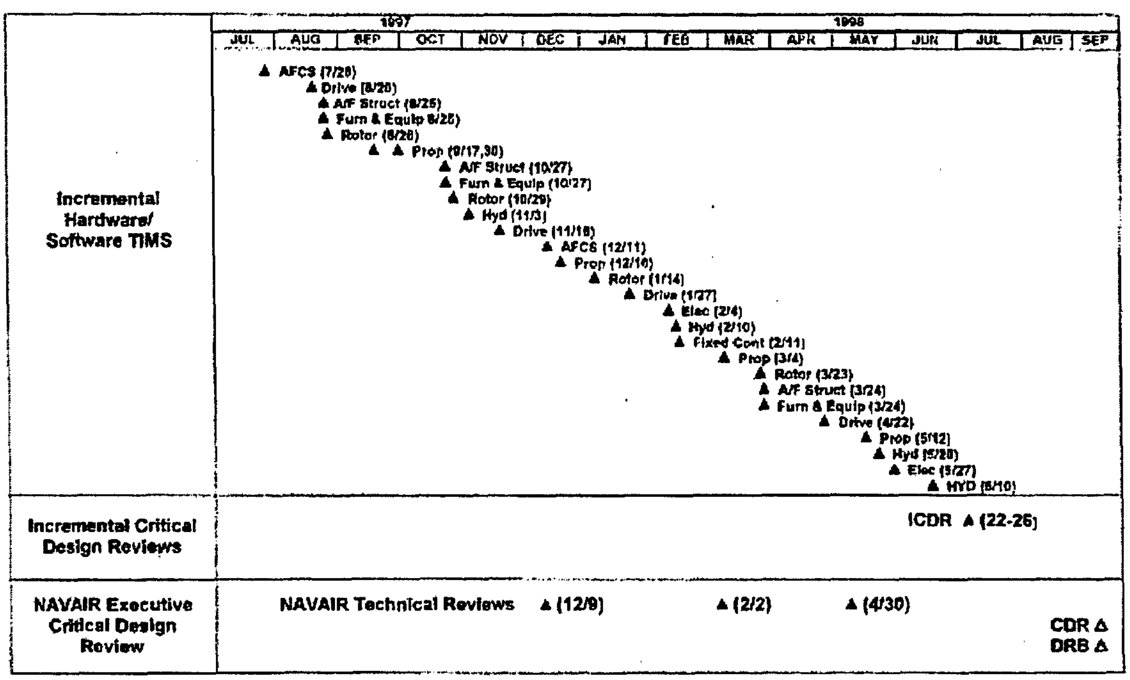


Fig. 6. The roadmap to CDR using TIMS.

Table 1. Tracking technical status.

	Performance ratio at PDR (June 97) UH–1Y	Performance ratio at PDR (June 97) AH–1Z	Performance ratio at CDR (Sep 98) UH–1Y	Performance ratio at CDR (Sep 98) AH–1Z	Desired direction
Weight*	1.003	0.998	0.985	0.977	⇓
Recurring costs*	1.012	1.002	1.035	0.979	⇓
Unscheduled maintenance costs*	1.083	1.022	0.984	0.944	⇓
Reliability*	1.061	1.161	1.309	1.381	⇑
Maintainability*	0.740	0.700	0.696	0.640	⇓
Key performance parameters**					
Payload	1.074	1.100	1.092	1.121	⇑
Maximum continuous speed	1.110	1.029	1.114	1.043	⇑

* Relative to Plan to Perform.
** Relative to requirement at delivery.

Commonality as a Strategy
The H–1 Upgrades Program presented a unique opportunity for the IPTs to maximize commonality between the AH–1Z and the UH–1Y. Commonality was recognized by all team members as being beneficial to the Program; however each of the disciplines within the IPTs viewed it as being important for different reasons. For example,

- The designers and planners saw it as a way to minimize the number of drawings that had to be created and, hence, a way to reduce budget and schedule requirements.
- The cost analysts viewed it as a way to reduce recurring costs because of the increased quantities of common items.
- The tool designers saw commonality as a way to reduce the number of tools.
- The logistician saw it as a way to minimize LSA tasks, manuals, and training.
- The Customer viewed commonality as a way to reduce costs and real estate needs aboard U.S. Navy ships (because of fewer spares and less support equipment).

This emphasis on commonality resulted in a significant number of components on the two aircraft being identical — hence the term "identicality" was used to describe them. As illustrated in Fig. 7, the AH–1Z and UH–1Y are over 50% common by weight and cost; perhaps even more importantly, about 85% of the maintenance-significant components are identical. This reduces the logistics tail, training, foot-print, and cost.

IMPROVED MISSION EFFECTIVENESS

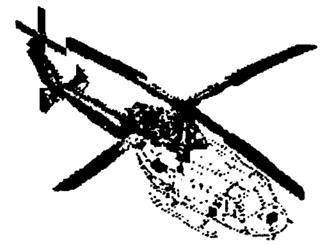
The purpose of the H–1 Upgrades Program is to improve the mission effectiveness of the AH–1Z and UH–1Y in ways that are cost effective over the life cycle of the aircraft. This enhanced effectiveness is the result of improvements in five major areas—propulsion, integrated cockpit, survivability features, improved weapons capability, and the targeting sight system. Improvements are summarized in Fig. 8. The "upgraded" helicopters are new with "zero-time" airframes and the following new components:

- Main and tail rotors.
- Main transmission and 90-degree gearboxes.
- Landing gear.
- Transmission support structure.
- Airframe stretch with new primary structure (UH–1Y).
- Crew and troop seats.
- Integrated avionics.
- Auxiliary power unit.
- Fuel system (UH–1Y).
- Engine digital electronic control unit.
- Weapons pylons with internal fuel (AH–1Z).
- Hydraulic system.
- Electrical system.
- State-of-the-art integrated wiring.
- Target sight system (AH–1Z).

In this section, these improvements and their impact on the effectiveness of the aircraft are described. Features to marinize both aircraft for the U.S. Navy shipboard environment are also discussed.

Propulsion System
The propulsion system, as discussed on the following pages, includes the rotors, drive system, engines, fuel systems, and auxiliary power unit. Improvements in hydraulics, controls, and other subsystems also increased effectiveness because of simplifications that reduce weight and cost and improve reliability; but these are not discussed in detail here because of space limitations The propulsion system is identical on both the AH–1Z and the UH–1Y. The propulsion system design incorporates

- Glass cockpit controls and displays
- Main rotor
- Drive system
- Hydraulic system
- Electrical generation and distribution system



- APR-39 radar warning
- Tailboom
- Horizontal stabilizer
- Chaff/flare dispensers
- Tail rotor
- Intermediate gearbox
- Tail rotor drive shafts
- AVR-2 laser warning set
- Auxiliary power unit
- 90-degree gearbox

- T700-GE engines
- Infrared suppressors
- Combining gearbox
- Rotating controls and actuators
- Wiring interface assemblies
- SCAS computer
- DCS-2000 radios
- Multifunction displays
- AAR-47 missile warning system

- APX-100
- SCAS actuators
- ARN-153 TACAN
- Oil cooler
- D/C – A/C inverters
- Main transmission
- Ultra low maintenance battery
- Crashworthy crew seats
- TAMMAC

Fig. 7. List of identical components for AH–1Z and UH–1Y.

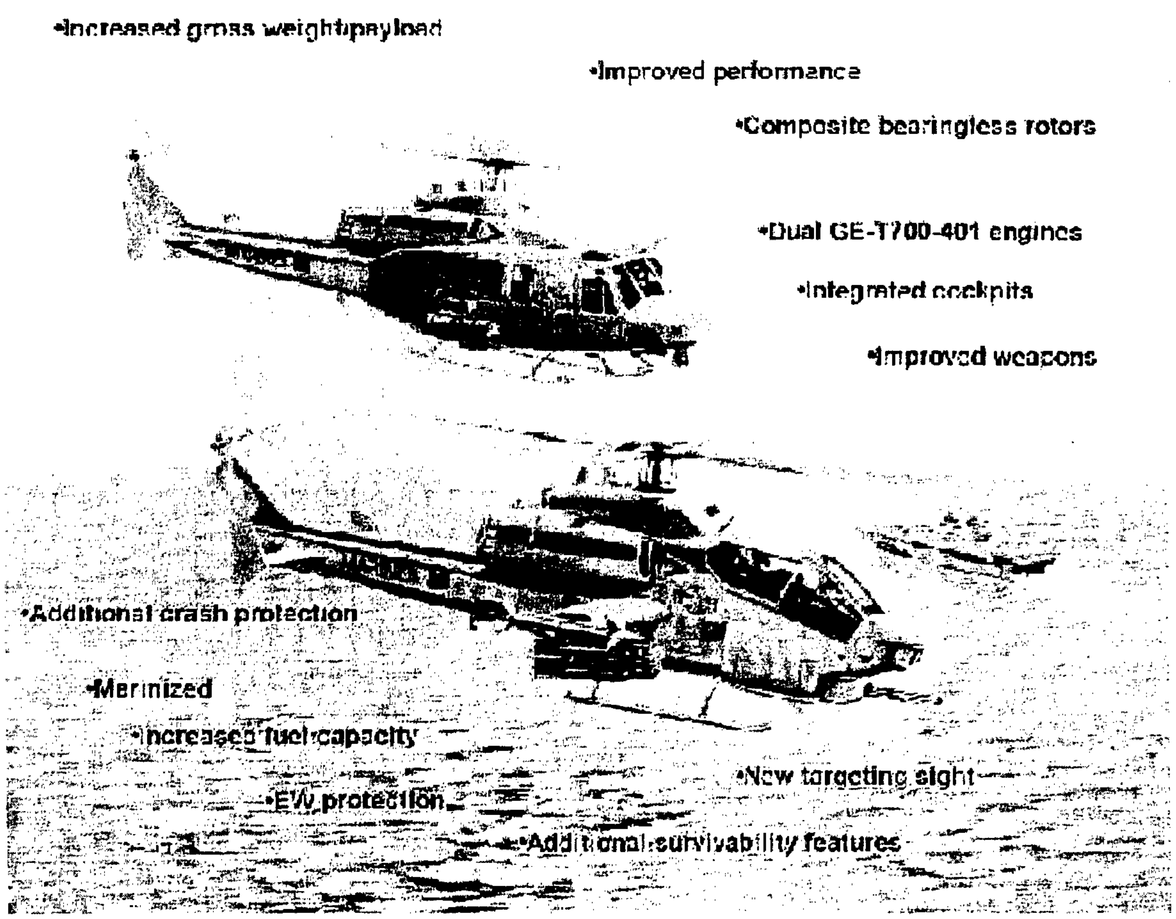


Fig. 8. Summary of improvements for enhanced mission effectiveness.

the latest technology in materials and design concepts while balancing these with weight and cost constraints.

Rotor
The main and tail rotors are shown in Fig. 9. Both rely on advanced composites to provide durable, damage-tolerant designs where the flexing of composite members, not bearings, is used to accommodate blade pitch change requirements. The main rotor is derived from the proven Model 680 rotor concept used on the 4BW (AH–1Z prototype) and on the production Bell Model 430.

The main rotor has reduced part count, is easily removable, and requires no lubrication. It is ballistically tolerant, flaw tolerant, and designed for 10,000-hour fatigue life. The blades are folded for Navy shipboard operation. The tail rotor has four blades with an integral tension–torsion strap that attaches to a fail-safe titanium hub. An elastromeric bearing is integral to the hub to provide for rotor flapping. Lubrication is not required.

Drive
The H–1 drive system is shown in Fig. 10. The main transmission and tail rotor gearbox are new for the H–1 Upgrade. The main transmission is rated at 30% more power to improve the performance of both the AH–1Z and UH–1Y. On the new cases, magnesium has been replaced with aluminum to reduce corrosion. The new gearboxes are designed with 30-minute run dry capability to reduce vulnerability to ballistic damage; they are also designed for a 5000-hour time-between-overhaul (TBO) to reduce the O&S costs to the Marines.

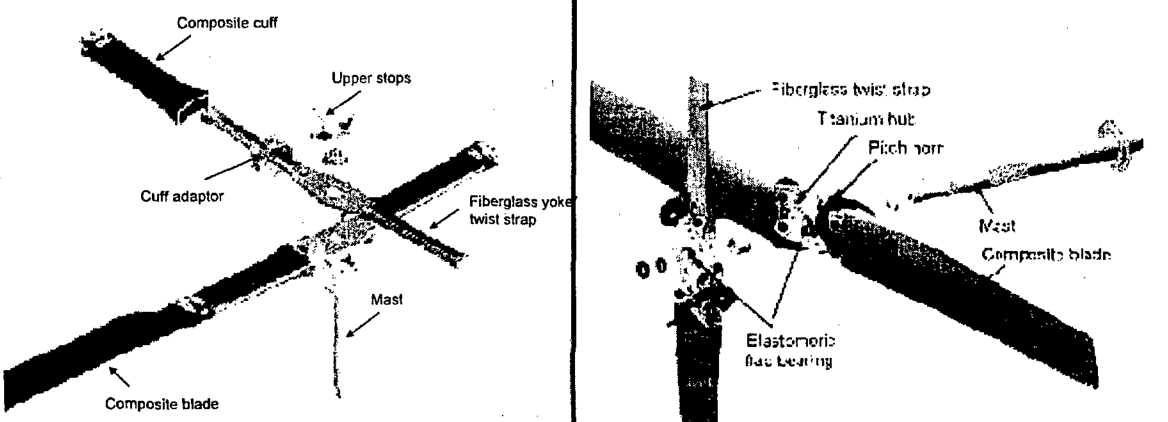
Engines/Auxiliary Power Unit
The H–1 engine and auxiliary power unit is shown in Fig. 11. The APU, provided by Sunstrand, is currently in the DOD inventory. This unit provides electrical power for system checkout, hydraulics to permit control movements for ground check and blade fold, and compressed air for starting the GE-T700-401 engines. The engines are used currently in the AH–1W and are modified slightly with a digital electronic control unit (DECU) for improved rotor speed control. The GE-supplied IR suppressor is also modified slightly to give better interface to the aircraft and to reduce exhaust gas temperatures.

Fuel
The fuel systems (Fig. 12) are improved on both aircraft—with increased capacity for additional range, ballistic protection, fuel cell inerting, and improved crashworthiness for enhanced survivability, as discussed later. One benefit of the propulsion system improvements is an increase in maximum hover gross weight and hence payload, so that additional fuel, ordnance, and speed is available. This means the aircraft can operate at extended ranges, get there quicker, have more time on station, and carry more weapons or payload for the Marines they support.

Integrated Cockpit
The heart of the H–1 Upgrade integrated cockpits is the Integrated Avionics System (IAS), supplied by Litton Guidance & Control Systems. The IAS uses powerful technology with large growth margins and open architecture combined with commercial base components to

- Bearingless
- Advanced airfoils
- 10,000 hr fatigue lives

- No lubrication
- Ballistically tolerant
- Simple, reduced parts count



Main Rotor

Tail Rotor

Fig. 9. H–1 main and tail rotors.

For new components
- Run dry
- 5000 hr TBO

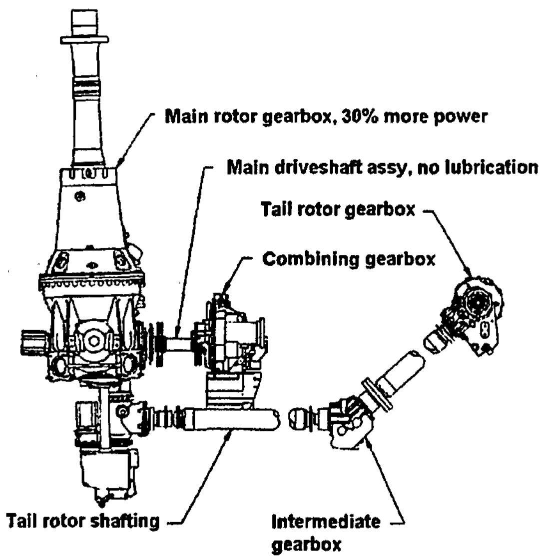
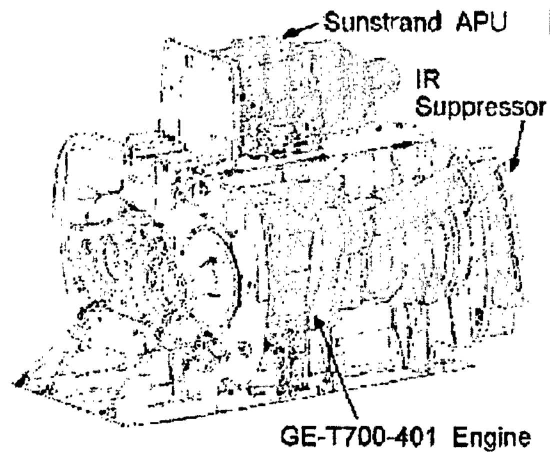


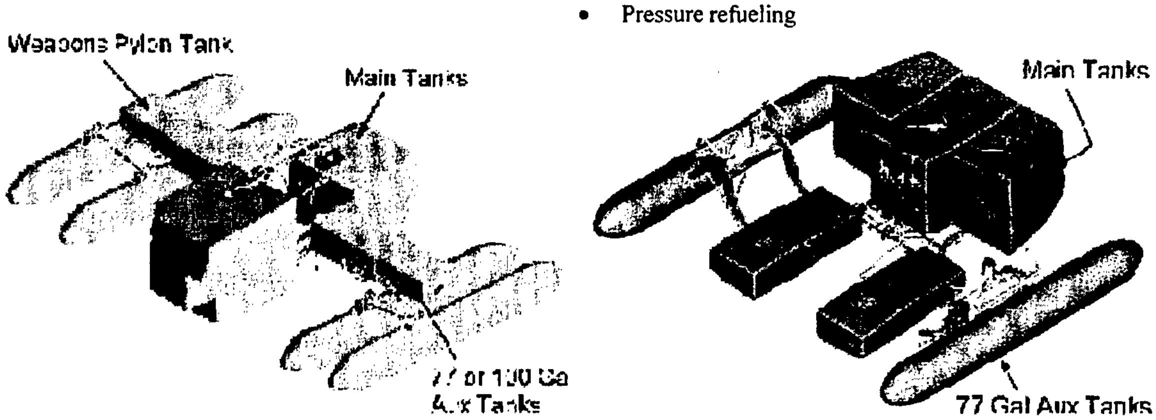
Fig. 10. H–1 drive system.



- Integral particle separation
- Fully marinized
- Self-contained lubrication

Fig. 11. H–1 engine/APU install.

- Self-sealing
- Crashworthy, break away fittings
- OBIGGS inerting
- Zero G capability
- Pressure refueling



AH–1Z UH–1Y

Fig. 12. H–1 Fuel Systems.

give the H–1 a cost-effective state-of-the-art system. Building on nondevelopmental items (NDI), the IAS is designed to accommodate upgrades in countermeasures and other systems, as they become available without expensive redesign.

The cockpit integration is a culmination of the efforts of multiple design teams. From aircraft subsystem sensors and controls, which are processed by Wiring Interface Remote Terminal (WIRT) computers, to advanced avionics systems integrated in the mission/weapon computers, the many sources of information required to fly and fight the aircraft effectively are made available to the aircrew in the functionally identical cockpits. Extensive design efforts were conducted to ensure the information and capabilities available to the pilots are presented in an intuitive and unambiguous format. The designers were faced with the task of making it all happen within the available cockpit space, and with the additional challenge of improving the pilot's exterior field of view.

The cockpits were designed to reduce pilot workload by (1) allowing easy access to information required and (2) automation of routine procedures. The cockpits are virtually identical, allowing the pilots to fully fight and fly from either station. The reduced crew workload permits the pilots a "heads out of the cockpit" level of situational awareness that allows enhanced safe operation of the aircraft, decreased vulnerability of the aircraft to threats, and more rapid, lethal responses to requests for close air support.

One example of automation is the execution of an immediate close air support mission. The mission brief is received digitally over the radio and is decoded and stored for retrieval in the mission computer. Once the pilot accepts the mission, the computer will provide steering to the assigned attack position that will have the aircraft in place with sufficient time to acquire the target and fire. As the aircraft is maneuvering into the attack position, the targeting sensor will be pre-pointed to the target coordinates and elevation. The computer will also use the range to target and selected weapon system to calculate stores time of flight and cue the pilot when to fire, allowing fire support "on target, on time."

The crew interface architecture is centered around the "all-glass" cockpits, shown in Fig. 13 for the AH–1Z, consisting of two multifunction displays (MFD), one dual function display (DFD), keyboard, Integrated Helmet Display Subsystem (IHDSS), mission grips, and hands-on collective and stick (HOCAS) controls. The glass cockpit allows the pilots' access to all tactical, flight, aircraft system, weapons, and targeting sensor information required. The crew vehicle interface design was based on the premise of not requiring the pilot to change his primary display setup to access flight and mission critical information or conduct routine in-flight tasks such as changing communication frequencies or changing navaids.

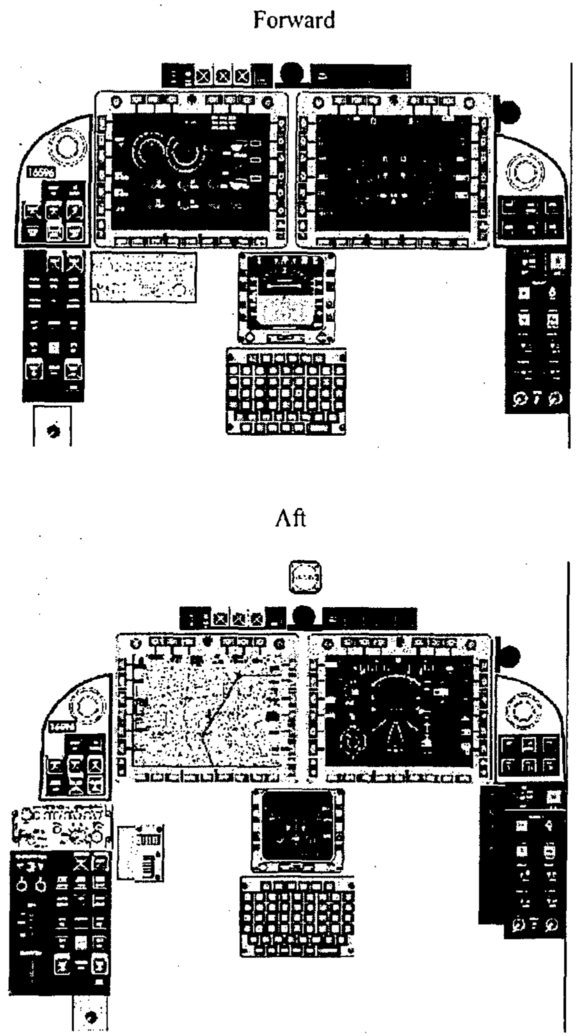


Fig. 13. The AH–1Z Cockpit Instrument Layouts

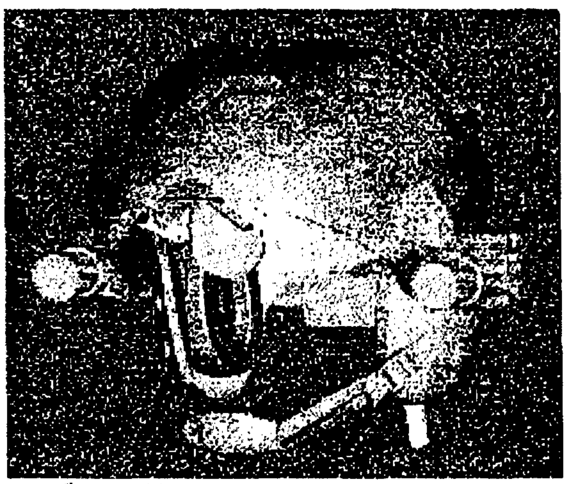
The primary displays depicted in Fig. 13 are the map/nav page, flight page, weapons page and the targeting page. The map/nav page is the primary navigation and steering cueing to the aircrew and provides overlays of the tactical situation. The flight page provides all attitude, airspeed, and altitude information to the pilot as well as the critical aircraft systems information of rotor speed, drive torque, and engine power available. The flight page essentially replaces the instrument panel gauges of a traditional cockpit. The weapons page allows rapid selection and intuitive viewing of the current state of the weapon selections and remaining stores. The targeting page allows selection of the Target Sight System (TSS) modes and viewing of either the color TV video or forward looking infrared (FLIR) imagery for detection and selection of targets. The other primary MFD pages provide detailed access for electronic warfare, detailed system information, communication, warnings/cautions/advisories, and tactical data communications (TDC).

The IHDSS (Fig. 14) provides the aircrew day and night heads up, heads out text and graphical symbols of critical flight, navigation steering, and weapons aiming information. The visor-projected information provided to the pilot allows normal operation of the aircraft without having to continually scan inside the cockpit for critical information. The integrated helmet tracker allows the helmet display to provide line-of-sight referenced displays that provide a "virtual heads up display" (HUD) for aircraft datum launched weapons and attitude display, off-axis weapon and sight cueing, and navigation steering cues overlaid on the real world.

The night vision cameras coupled into the IHDSS provide a high-resolution scene display to the pilot that is unequalled by any other HMD currently being developed. The cameras equal, and in some cases exceed, the performance of even the latest fielded direct view night vision goggles (NVG) at low ambient levels, particularly in urban environments.

The intuitive, easily accessed system controls and displays are further enhanced by the mission grips and HOCAS controls. These are presented in Fig. 15. The HOCAS controls allow the aircrew traditional flight control switch functions augmented by the new capability to control the MFD pages, select modes, and change radios and frequencies without having to release the flight controls. The following highlight some of the HOCAS features:

- Selection of any weapon system.
- Selection of systems, caution/warning/advisory, electronic warfare, and sensor pages for display, as well as return to the primary display.
- Selection of radio and changing preset communication frequencies.
- Selection and adjustment of automatic flight control system (AFCS) "autopilot" modes.



- 1st helo with night capable HMD
  - Dual image intensifier (I2) cameras
- Metal tolerant head tracker
- Dual CRT visor projects day or night symbology
- Provisions for FLIR/TV video on HMD
- Heads-up-display information overlayed on HMD image

Fig. 14. The AH-1Z Integrated Helmet System.

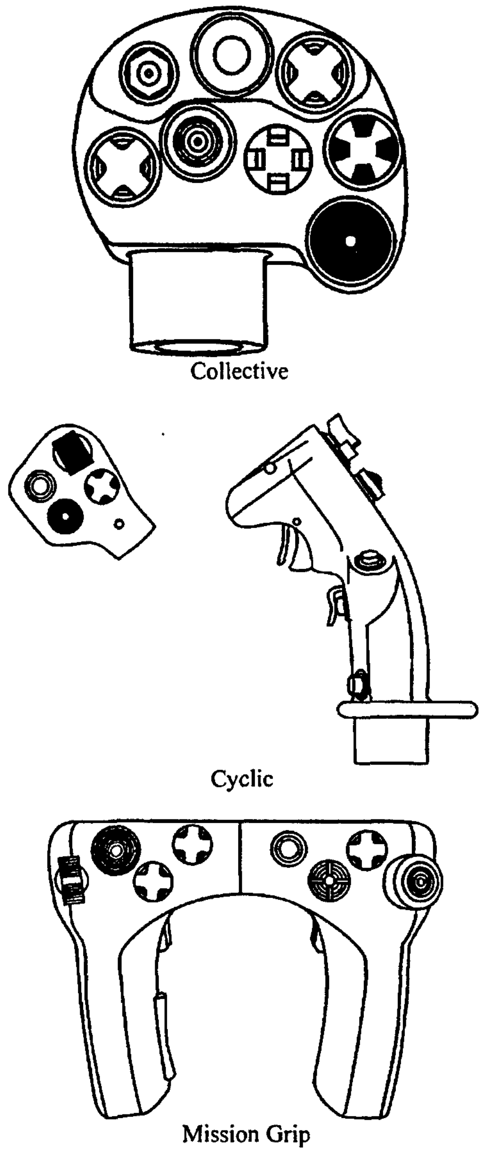


Fig. 15. H-1 HOCAS and mission grips.

The mission grips allow either pilot to fully operate the TSS and control weapon selection and delivery "hands on."

This description has focused on the AH–1Z configuration; however, most of the cockpit instruments and their functionality are identical on the UH–1Y, as shown in Fig. 16. The UH–1Y uses the same cyclic and collective grips as the AH–1Z, but a different targeting sensor and control grip. The grip is integrated into the avionics system and has identical control and display features when identical functions are selected. Currently, the UH–1Y does not incorporate the IHDSS, but a NVG-HUD is provided to display critical flight and navigation information "Heads out" during the more hazardous operating environment present at night.

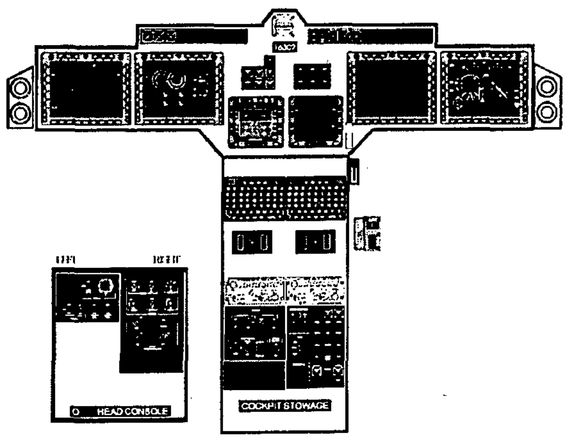


Fig. 16. The UH–1Y cockpit instrument layout.

SURVIVABILITY FEATURES

Mission effectiveness of the AH–1Z and UH–1Y has also been increased with design features to improve survivability in the battlefield (Fig. 17). Vulnerability to ballistic threats has been reduced with a number of improvements:

- The diameter of control tubes has increased to reduce vulnerable areas.
- The rotor systems have been designed for continued flight after penetration by rounds as lethal as 23mm HEI. Redundant load paths in the main and tail rotors enhance this feature.
- Self-sealing fuel tanks with powder panels are used to preclude fires after penetration by incinerary rounds.
- New gearboxes are designed with 30-minute run dry capability to prevent forced landing after loss of lubricant from ballistic penetration.
- Redundant load paths are provided in highly loaded airframe components, and redundancy in control actuators and other subsystems is used to provide for fly-home capability.

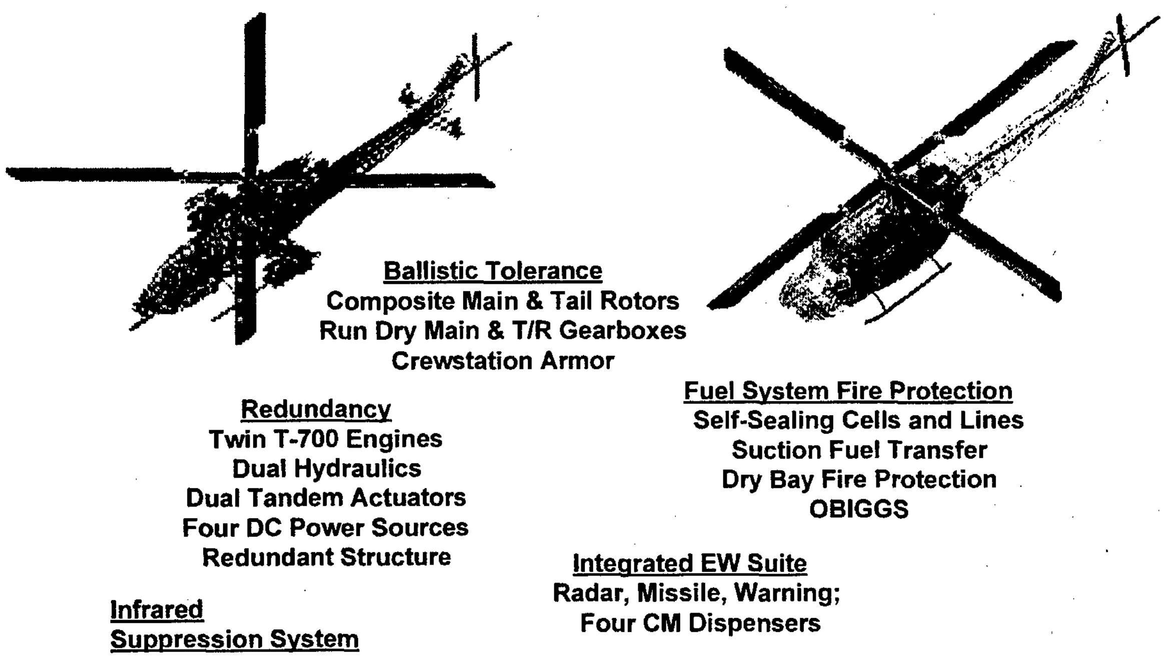


Fig. 17. H–1 survivability features.

The reduction in vulnerable area as a result of these design features is presented in Fig. 18.

The infrared signature of the aircraft has also been reduced, primarily with the improved IR suppression and exhaust shielding on the GE-T700-401 engines. The effectiveness of these improvements in reducing the signature of the aircraft below the specification requirement is presented in Fig. 19.

Active countermeasures are also included on both aircraft, and they are integrated into the avionics systems to improve their effectiveness. The number of chaff/flare dispensers has been increased to four on both aircraft, and placed strategically on the airframes to increase their effectiveness in all quadrants. Dispensing of these countermeasures can be manual or automatic with the integrated avionics package, since they are coupled with the radar/missile/laser warning systems.

Additional design features, shown in Fig. 20, protect the aircraft, passengers, and crew in the event of a hard landing. The AH–1Z and UH–1Y landing gears are designed for landings up to 12 ft/s without damage to the aircraft. In addition, large mass items, including fuel cells, are designed to remain attached to basic aircraft structure for crashes up to 20*g* fore-and-aft or vertical or 10*g* lateral. In the event of a crash, stroking seats provide extra crew and passenger safety on both aircraft.

All of these improvements help the Marines stay in the fight while ensuring that damaged aircraft make it home and can be repaired for follow-on missions.

MARINIZATION

Features to protect aircraft operating in the maritime environment experienced by the Navy and Marines are expensive to incorporate if they are not included as a part of the basic design process. Both the UH–1Y and the AH–1Z are designed to operate effectively in this environment. Features incorporated in both aircraft, shown in Fig. 21, include corrosion resistant composite main and tail rotor systems; aluminum cases on all the new or modified gearboxes; elimination of many aircraft structure joints through the use of high-speed machined

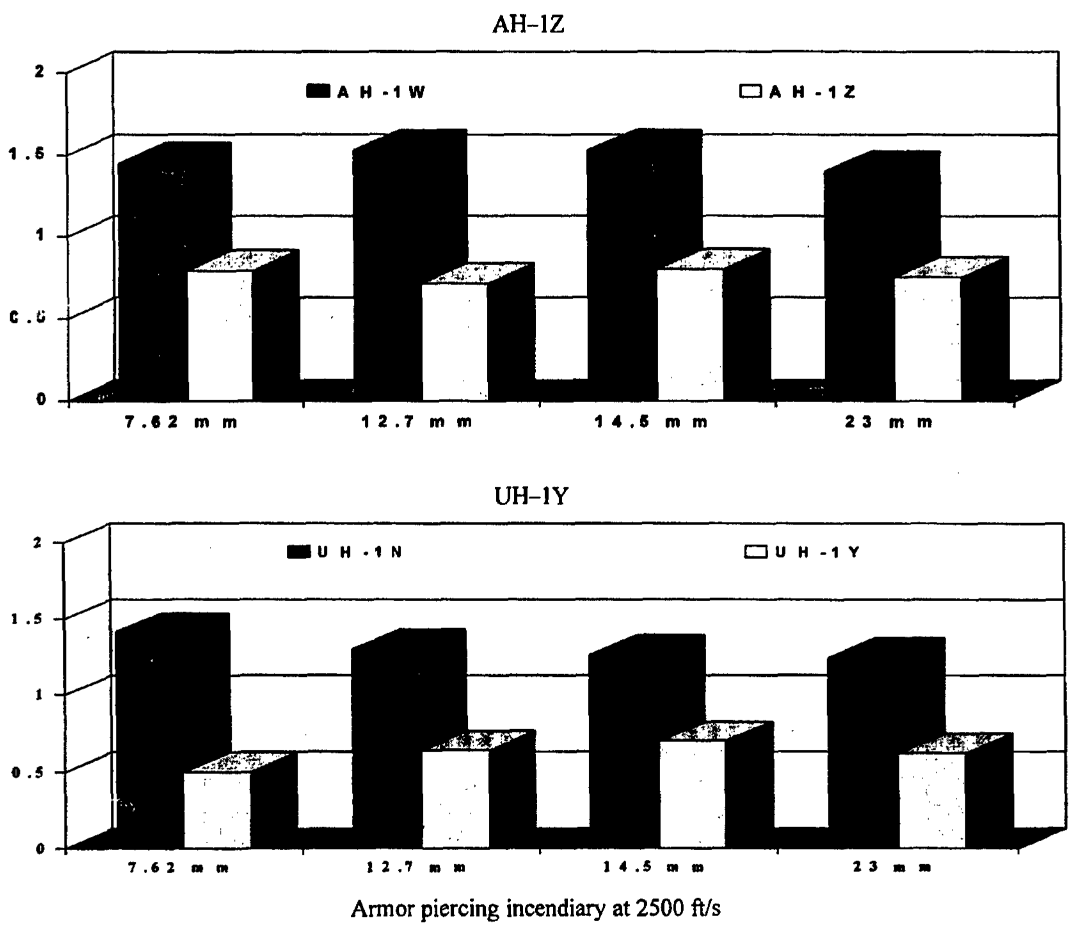


Fig. 18. AH–1Z and UH–1Y ballistic vulnerable area improvement.

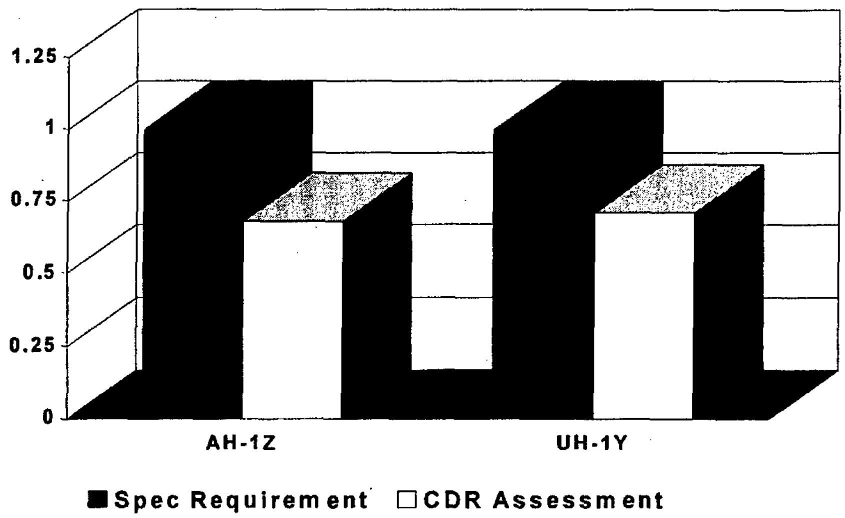


Fig. 19. Improved IR signature of H–1 aircraft.

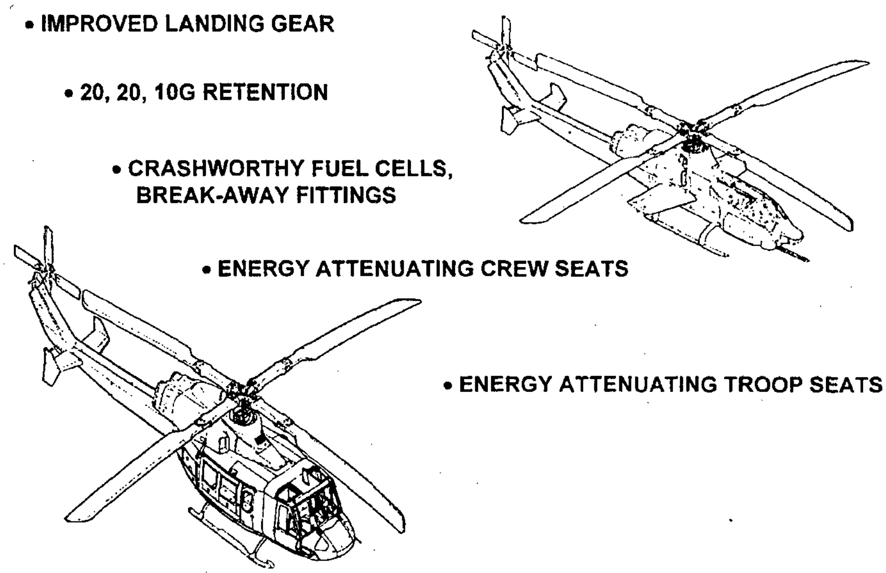


Fig. 20. Improved crashworthiness features

components and treatment of the remaining joints to resist corrosion; marinized engines; and electronic components designed to operate and survive in the high energy electromagnetic fields found near Navy ships. In addition, other aircraft design features, such as blade fold, 30-degree turnover angle, and tiedown provisions for high wind and rough sea conditions, enhance the operation of the H–1 aircraft in this environment. These features not only extend the life of the aircraft, they reduce the amount of time the Marines must spend maintaining the aircraft.

IMPROVED WEAPON SYSTEM

The new AH–1Z weapons/ordnance array is the greatest of any helicopter in the world today. These ordnance options are illustrated in Fig. 22. The existing 20-mm gun with 750 rounds of ammunition is being retained, but the accuracy is improved with the Litton integrated avionics package combined with a low-airspeed system from Marconi Electronic Systems. The gun is controlled by either crewmember, using either the helmet mounted display or the mission grip.

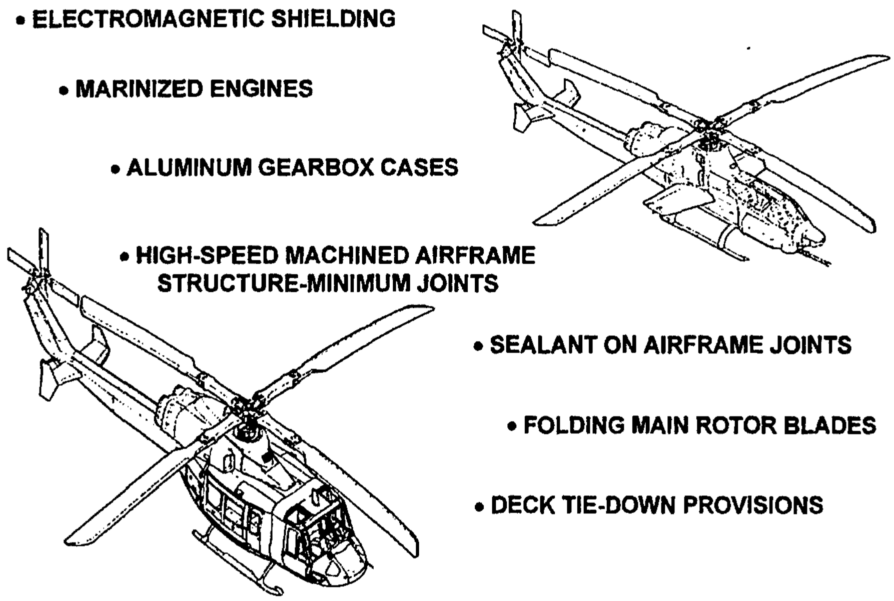


Fig. 21. Marinization/shipboard operating enhancements.

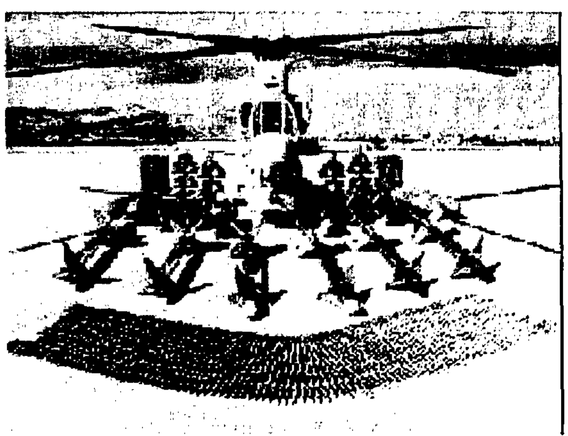


Fig. 22. The AH–1Z weapon suite.

On the AH–1Z, four new universal weapons stations can accept the following ordnance types:

- Sidewinder
- Sidearm
- Stinger
- HELLFIRE
- Rockets
- Longbow HELLFIRE and Maverick

The four stations can also be used for auxiliary fuel to provide long-range ferry capability. In addition to the four universal stations, two additional stations are incorporated into the weapons pylon tips to accept either the Sidewinder, Sidearm, or Stinger.

On the UH–1N, provisions are made to mount the Marine's DAS mount, which has the capability to accept 50-caliber or 7.62mm machine guns and the 2.75-inch rocket pod.

Targeting Sight System

One major element of the improved mission effectiveness of the AH–1Z is the new targeting sight system (TSS), provided by Lockheed Martin. The TSS brings state-of-the-art, third-generation FLIR targeting for the Marine Corps. When combined with the Integrated Avionics System from Litton, the TSS gives the AH–1Z unsurpassed capability to fight and survive in the battlefield of the 21st century.

The TSS, shown in Fig. 23, mounts to the nose of the AH–1Z through an interface structure that supports the turret assembly. A five-axis gimbal provides the motion required. The payload is supported on this gimbal and isolated from helicopter and gunfire vibrations. An integral boresight module attaches to the rear of the interface structure.

The turret assembly, made by WESCAM, and the payload details are shown in Fig. 24. The gimbal is designed to accommodate each of the major components as modules so that future upgrades can be implemented without major redesign.

The heart of the TSS is a third-generation, mid-wave infrared, staring-focal-plane-array FLIR. This FLIR has an 8.55-inch diameter aperture and enhanced image processing that result in increased identification,

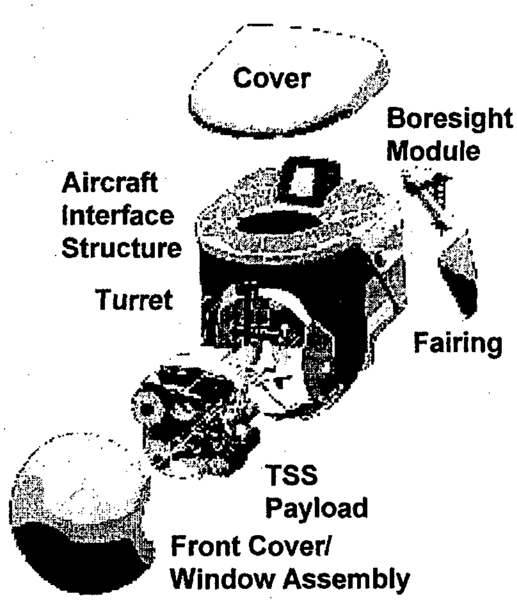


Fig. 23. The AH–1Z targeting sight system (TSS).

recognition, and detection range with sharper image resolution and less sensitivity to weather. Four fields of view are provided to aid in detecting, identifying, and tracking potential targets.

The TSS also has a color TV made by Sony to aid in target detection. The TV has continuous optical zoom, which gives magnifications up to 21×, selectable from the mission grip. Performance filters for glare reduction and haze penetration can be selected by either crewmember.

A Litton laser, used on the F-16 LANTIRN pod as well as the TSS, is installed on the gimbal for designation and for rangefinding. The laser has an integral eye-safe mode that can be used for enhanced safety during training. A laser spot tracker is also included to enhance the capability of the AH–1Z to track or designate targets during high-workload, battlefield environments. A Litton LN200 Inertial Measuring Unit (IMU) is also mounted on the gimbal to give precise inertial coordinates for interface with the Integrated Avionics System and geopositioning of aimpoints for GPS guided weapons.

Operationally, the TSS can be controlled by either crewmember, either manually or automatically, through the heads-up-display (HUD) on the helmet. It also interfaces with the TAMMAC (digital map) for pre-pointing to selected targets. In addition to the laser spot tracking mentioned above, the TSS also performs scene tracking in both the FLIR and TV modes and is capable of prioritizing and tracking up to 4 targets simultaneously.

The third-generation FLIR and the laser give the AH–1Z unparalleled capability to detect, recognize, identify, and designate targets. A comparison to existing systems is presented in Fig. 25. The capability of the TSS to address targets at the maximum range of several missiles is

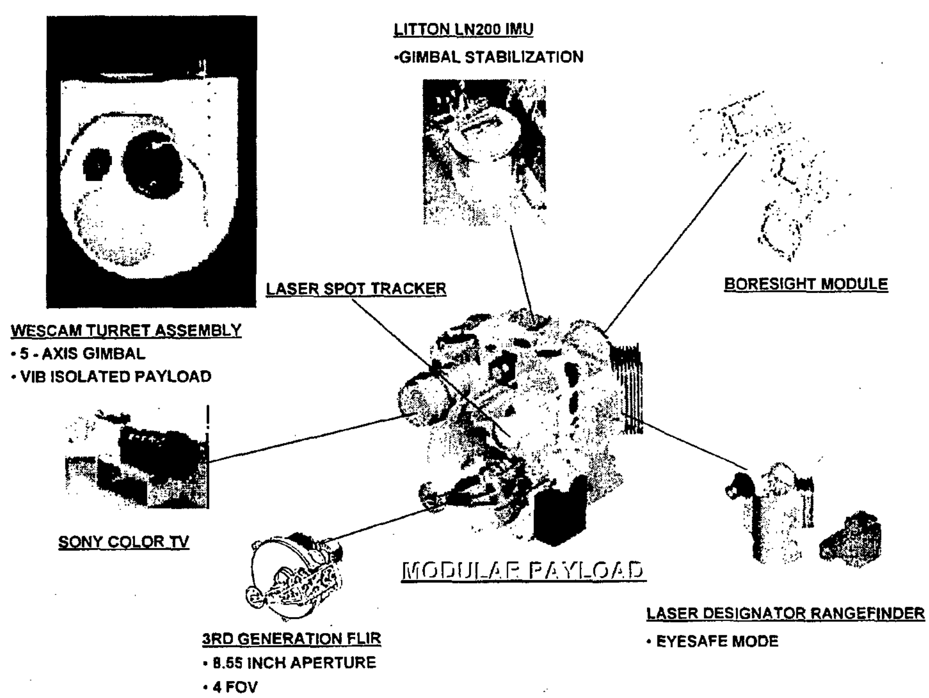


Fig. 24. TSS details.

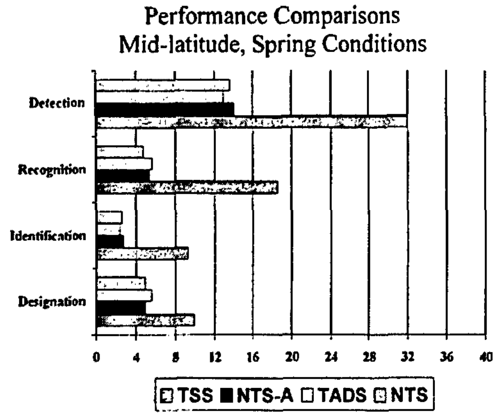


Fig. 25. Range comparison for targeting sight systems.

shown in Fig. 26 and compared to first- and second-generation systems. The increased performance of the TSS at these ranges gives the AH-1Z and the Marines the ability to make maximum use of the capability of these systems. The TSS allows the Marines to rapidly identify and engage targets at extended ranges, increasing their lethality over a greater area while reducing the vulnerability of the aircraft to engagement by the threat.

SUMMARY AND CONCLUDING REMARKS

As a part of the Marine Corps strategy to provide war-fighting capability through the first quarter of the 21st century, Bell Helicopter and the Marines are using Integrated Product Teams to upgrade the UH-1N utility aircraft and the AH-1W gunship to new configurations—the UH-1Y and AH-1Z.

The upgrade program is structured to give the maximum capability achievable within constraints of development and life-cycle costs, and CAIV studies are used to address potential savings against program requirements.

The resulting H-1 configurations have significant improvements compared to the current aircraft. Both aircraft have been designed to operate in the harsh maritime environment required for the Navy and Marine Corps missions. New dynamic components, combined with increased power in the main transmission, increase the performance of both aircraft to improve both speed and payload. The increased power also accommodates improvements to reduce vulnerability to ballistic and infrared threats. Crashworthiness is also improved with large mass retention at higher crash load factors and energy-absorbing seats and landing gears.

New integrated cockpits for both aircraft have state-of-the-art displays, and the Bell/Government/Litton cockpit team has defined cockpit functionality and man/machine interface to drastically reduce pilot workload and improve situational awareness. On the AH-1Z, an integrated helmet display subsystem with night-vision cameras provides day and night heads-up pilotage capability to improve the effectiveness of the aircraft.

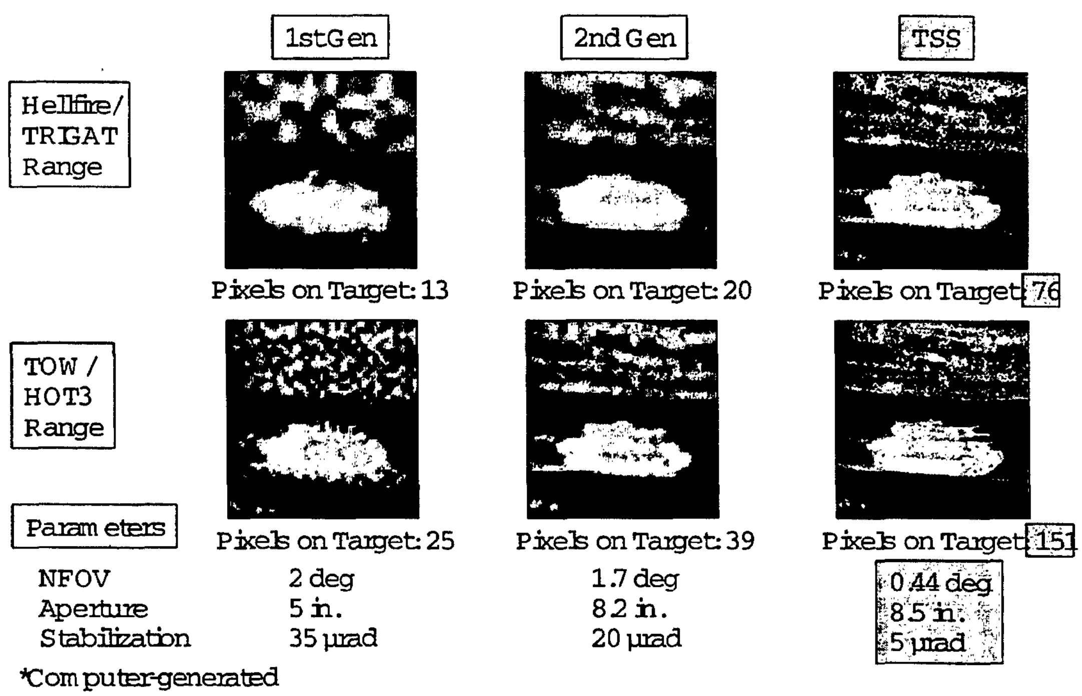


Fig. 26. The impact of FLIR technology on performance.

The AH–1Z also has a new target sight system with third-generation FLIR, color TV, and both tactical and eye-safe laser. With the sight, the AH–1Z identifies and designates targets out to the maximum kinetic range of the weapons it carries.

The H–1 Upgrade designs presented a unique opportunity to incorporate common components in the two configurations and in the final design, about 85% of the components that require maintenance are identical. Over the life cycle of the aircraft, this identicality has a tremendous paypack in reduced costs to maintain and support the aircraft.

The new AH–1Z and UH–1Y are modern, zero-time aircraft designed to operate effectively the next 30 years. The UH–1Y is the most capable light, multi-role helicopter in military service. The AH–1Z is the premier attack helicopter on the battlefield, carrying the widest array of weapons and equipped with the most capable target sight system in the world. The AH–1Z and UH–1Y provide the most potent and cost effective attack and utility combination for the 21st century warfighters. Both aircraft are currently being fabricated, with many components in test to support first flight next year. Production deliveries begin in 2003 with 180 AH–1Z and 100 UH–1Y scheduled to be delivered to the Marine Corps.

The Tornado GR4 Programme -A New Approach

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Summary

The growing costs of new weapon systems will encourage potential customers to consider upgrading their existing fleets. Today's aircraft will therefore be expected to remain longer in service and counter the threats of the future. Industry will need to adapt from developing and manufacturing new weapon systems to finding ways to improve the capability of an existing asset to maintain a deterrent in a higher technological environment. According to the 1997 British Aerospace Military Aircraft Value Plan 'The upgrade and re-life of existing aircraft is a valuable market opportunity – over the past five years the upgrade of existing assets has accounted for 16 per cent of the total value of combat orders world-wide'.

The RAF's IDS (Interdictor Strike) Tornado aircraft are expected to have a service life-span of up to 40 years and to ensure their combat effectiveness are currently undergoing a Mid Life Update (MLU) - the largest of its kind in Europe. The Mid Life Update programme returns 142 IDS Tornado aircraft to industry and upgrades them to a new variant, designated Tornado GR4/4A, which will become the new common standard for the RAF IDS aircraft.

The £1bn programme is split into three contractual elements – development, production embodiment and support. Panavia, the industrial partnership consisting of Alenia, DASA and British Aerospace brought together originally to design, develop and manufacture Tornado aircraft, is the prime contractor for the Development contract but British Aerospace lead for the Production Embodiment and Support contracts.

The Tornado MLU programme had a difficult start as the world socio-political environment changed but has emerged as one of the success stories of British industry.

The aircraft will receive during the embodiment programme system enhancements including a forward looking infra red system, an improved defensive aids system, improved and full Night Vision Goggles compatible cockpit displays, and the ability to carry a wide range of new weapons. This will provide a baseline standard for further upgrade improvements grouped into packages. Each new package will be introduced to the aircraft approximately every 18 months. Due to the flexibility of the approach taken by the team working on the programme it has been possible to encompass some additional operational requirements onto the aircraft as they pass through the MLU embodiment process.

This paper will provide an introductory overview of the programme looking at the historical backcloth, the three contract elements, and how we are tackling the future requirements of our customer. Specifically the experiences encountered by British Aerospace and it's partners, and how the Mid Life Update programme has stimulated innovative approaches to improve the responsiveness to customer demands. There has been a direct correlation between performance on the Programme and the level of team working that takes place. This is very encouraging to the programme with the continuing series of package upgrades planned over the next few years.

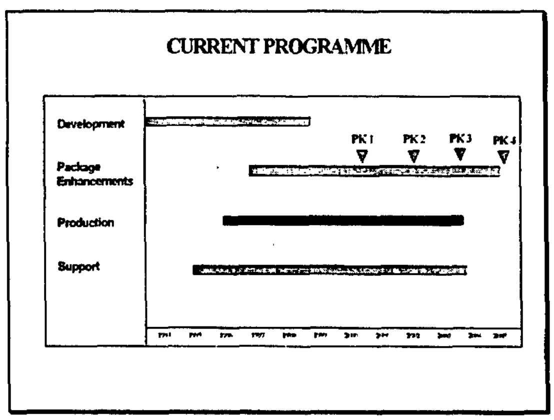

Figure 1 Tornado GR4 Programme

Finally the paper considers why an update for the Tornado was the right approach for the RAF in its quest to maintain an effective capability to match the defence needs of the United Kingdom in the early 21st century.

Historical Overview

The first discussions of a Multi-Role Combat Aircraft, the project from which Tornado emerged, took place in 1969 and involved a number of European countries. Many of these countries dropped out but three remained to design, develop and manufacture the swing-wing aircraft. The first Tornado GR1 aircraft entered service

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

with the Royal Air Force in 1981. The last Tornado aircraft built was delivered to the Royal Saudi Air Force in September 1998. Within the UK, the RAF use the aircraft primarily for Air Interdiction, Offensive Counter Air and Tactical Air Reconnaissance roles, and SEAD (Suppression of Enemy Air Defences) following the introduction of ALARM in 1990.

The Tornado aircraft is in-service with the Air Forces of Germany, Italy, Saudi Arabia and the United Kingdom. Panavia have built nearly one thousand Tornado aircraft. In the United Kingdom there are two main variants - the IDS (Interdictor Strike) and the Air Defence Variant (ADV). The UK IDS has three versions:

- GR1 - IDS
- GR1A - Reconnaissance
- GR1B - Maritime Attack

In addition to this the Royal Air Force have fitted specific equipment and carried out special order only modifications to certain aircraft to meet an immediate operational requirement which has resulted in a situation where there are very few aircraft to the same standard.

The Tornado GR1 is a proven performer, with successful operations in the Gulf War, has automatic navigation and weapon aiming, a very comprehensive passive and active Electronic Warfare capability, and can carry a wide range of weapons. The aircraft is optimised for all weather, day or night low level operations, and is heavily dependent on its automatic terrain following radar.

However, already by the mid 1980's studies were underway involving Germany, Italy and the UK on how to improve the aircraft's capability in view of the technology advances since the aircraft had been designed and developed in the early seventies. After some delay eventually the UK decided to go ahead alone with a requirement 'To enhance the capability of the Tornado GR1 aircraft to find and successfully attack its targets in all weather and reduce its vulnerability to attack'. This was Staff Requirement (Air) 417.

Specific areas of improvement highlighted were:

- To achieve improved covert night operations. The Tornado GR1 is very good at keeping low and out of sight behind hills but in bad weather has to use it's Terrain Following Radar and hence potentially leaving itself vulnerable to being tracked by opposing forces.

- To improve the aircraft's capability to fix positions and target locations for navigation and weapons aiming.

- To provide additional growth capability. The on-board computing capability is limited by modern standards.

- To improve supportability of the aircraft. As the Tornado's went through their original build programme the aircraft was consistently improved leaving a legacy of the three versions - trainer, strike, and reconnaissance aircraft - each with a range of different build standards. Additionally the RAF has incorporated numerous Special Trial Fits (STFs) and Special Technical Instructions (STIs) on specific aircraft. Consequently the logistic support and fleet management of the aircraft in service is very management intensive, which has also proved a major management challenge in the MLU Return-To-Works programme; this is discussed later.

The initial studies led to the development stage of the Mid Life Update programme starting in 1989. To meet the stated requirement the development work on the upgrade programme can be split into a number of areas:

- Introduction of a new avionics architecture built around a 1553 databus.

- New sensors & Displays consisting of a Forward Looking Infra-red sensor, a Pilot's Multi-Function Display with digital map, Wider angle HUD, Computer Symbol Generator, Video recording System and a Computer loading System.

- New Armament Control System consisting of a Stores Management System, a Weapon Interface Unit linked to a 1553 databus within a 1760 interface.

- A Night Vision Goggle compatible cockpit.

- Terrain Reference Navigation / Terrain Following Display / Terrain Following Switching & Logic Unit / Covert RadAlt.

Development work started in earnest but in the world some momentous events were taking place with the ending of the cold war. The original plan to embody the MLU standard onto the Tornado aircraft was to incorporate it into the last batch of aircraft to be built and retro-fit the earlier builds. However, this plan was thrown into disarray by the cancellation of the last batch buy from the UK. This left a hiatus over how to embody the MLU standard into the Tornado fleet.

The IDS Tornado's first operational use came with the

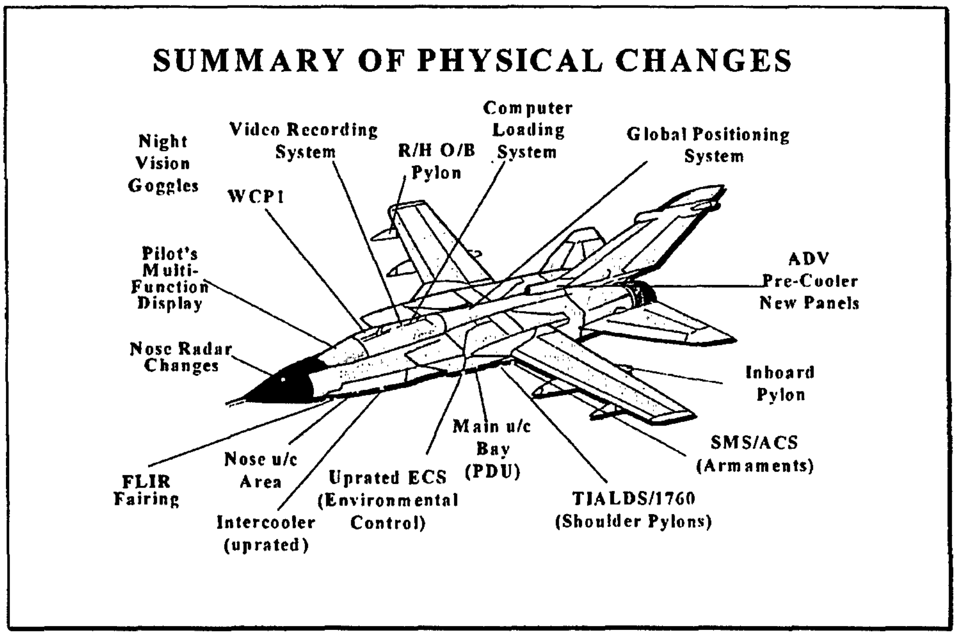

Figure 2 – Summary of Physical Changes

Gulf war where the aircraft carried out some of the toughest missions during the conflict - low-level attacks at night against heavily defended targets. The lessons learnt from the Gulf War emphasised that the sensors were optimised for low level operations. At night the crew were blind to other aircraft resulting in tactics having a heavy reliance on timing that gave little flexibility to evade and safely avoid air and ground threats. Once operations were moved to medium level there was a greater reliance on precision weapons and illuminators

On the domestic political front two government reviews took place – 'Options for Change', and 'Front Line First'. These resulted in MLU being under severe financial pressure not least because the politicians were looking for savings from the Defence budget, the so-called peace dividend, as a result of the collapse of the Warsaw Pact, but also the embodiment strategy was still not clear. In addition it was desirable to incorporate the Gulf War lessons. This led to a reassessment of the requirement to take the Tornado through to 2018. The solution resulted in what was to become MLU '93 and Production Embodiment would take place through a return-to-works upgrade package for 142 aircraft at Warton.

Despite the medium level lessons learnt in the Gulf the RAF decided that covert low level penetration remained the core requirement. The main deletion from the original MLU in hardware terms was the Terrain Reference Navigation System and it's associated equipment. In its place a Global Positioning System was introduced to ensure the required capability was met. The main additions to the programme were a TIALD (Thermal Imaging Airborne Laser Designator) system and a MEGTF (MLU Enhanced Ground Test Facility).

Whilst development activities were ongoing the Tornado GR1 had a number of software enhancements which were outside the scope of the original MLU development contract. These software additions had now to be somehow taken into account and incorporated.

The most important aspect of MLU '93 is that in addition to the basic enhancements of MLU, the flexible design created the foundation to incorporate future developments to the aircraft's capability. This is particularly relevant to the introduction of new smart weapons such as Brimstone and Storm Shadow scheduled for early in the 21st century.

Development

At the time of the initial negotiations for the development contract on MLU the MoD were in the process of moving away from cost plus contracting. The MoD and industry were learning about fixed price contracting when the Development contract was negotiated. The impact meant that the work content had to be fixed to provide a fixed price. Therefore certain actions were placed so that the Tornado GR1 aircraft was updated from as common a standard as possible. Remember each aircraft had been built to a slightly different standard and the RAF had also made some changes of their own to meet specific operational requirements. A baseline standard was agreed together with a 'Minimum Modifications List', which lists all the modifications that had to be on the aircraft when the RAF returned them to industry was included in the contract documentation. This solution meant that some modifications would have to be removed before the aircraft entered the MLU programme, an approach that suited the contractor since it provided a firm baseline for the development work. However, as development work progressed, any change, which is inevitable at this stage of a project, could only be carried out by an amendment to the contract.

The RAF found this one of the most frustrating areas since development on the Tornado GR1 aircraft continued to take place providing capability enhancements in isolation to the GR4 development programme. One such example is the carriage of Sea Eagle where some of the Maritime Tornado's had been upgraded to carry the weapon via the STF route. Under the terms of the contract this capability had to be removed before the aircraft entered the MLU programme, and would not be part of the MLU upgrade programme. Hence in this particular area the aircraft would be returned to the RAF at a lower capability than at which it left the Service. The RAF was not amused! This has been resolved by Package 1 that introduces Sea Eagle onto Tornado GR4.

Industry preferred to have no change since it distracted the engineers away from the task. The exception to this is where there is a need to undertake some additional work, for instance testing, to ensure compliance to the contract specification. For example the engineers identified the need to do more testing on the cockpit lighting mock-up as a result of making some minor equipment changes to the cockpit panels.

Although availability of hardware is important the speed of the development programme is driven by how quickly software development cycles can be achieved. A software load and two correction cycles have traditionally taken approximately three years to undertake. Therefore any change involving the integration of new avionics equipment, according to the working processes at the time, could only be introduced at three yearly intervals without disrupting and hence potentially risking the completion of the original software load.

As one would expect once the development programme had been stabilised with MLU '93 there were a number of issues that were identified as potential risks to the time scales of the contract. One of the continuing challenges to the update programme has been the difficulty encountered with TIALD development. The time scales available for its introduction onto Tornado GR4 had been continually shortening. TIALD was in development with a different contractor and the customer was committed to delivering a fully functional TIALD pod to the programme. Further there had been a number of observations from the RAF when the first cycle of software was released - in the terms 'well I know I specified it like that but now that I've seen it and tried it I want something slightly different'. Consequently a decision was taken to change the development programme radically again with the introduction of Package '0'.

The introduction of Package '0' occurred in early 1996 when the customer formally redirected the programme. It took a year to finally agree all the changes to the contract amendment. Package '0' encompassed the required changes from the customer observations to the software generated controls and displays, and accommodated the delay in the availability of a working standard TIALD pod. Furthermore the customer was keen to incorporate as many other software changes that were a direct result of enhancements in the Tornado GR1 aircraft since the scope of MLU '93 had been defined. All the hardware development would now be completed by October 1997 as originally planned, with the exception of TIALD. However, a new software load was introduced to cover off the customer observations and incorporate the Tornado GR1 enhancements. This meant that the full MLU standard software would not be released until September 1998, thereby taking up the planned six months contingency on the programme.

The key driver behind the revised programme was to ensure no impact upon the production embodiment contract. The net result was that the aircraft would be delivered on time, October 1997, to the customer but initially only with an interim standard of software. This would only effect the first few aircraft.

In hindsight, such an approach was risky because on the first aircraft delivered, the RAF crew, including the ground crew, would only see the 'work-arounds' undoubtedly leading to some frustrations because certain functionality was missing. Consequently all the parties involved with the decision, including the various elements of the MoD and the RAF, visited the main operating bases and explained to the RAF personnel who were receiving the aircraft what was happening on the project, what to expect and their role in the process. This proved a very useful exercise and in the process many of the urban myths and unfounded opinions were dispelled. The end user now knew what to expect when the aircraft arrived.

Additionally, once the aircraft arrived at the main operating bases a member of the development team was located with the RAF crews to assist in resolving any issues that may arise.

This paper has been written around the presentations given.

Not only were there concerns over the perception likely to be received from delivering the aircraft at an interim standard, but BAe and DASA did have a severe challenge in achieving the September 1998 deadline using the traditional software development process. The revised schedule required three years work to be completed in just over two years together with some additional effort to give a formal release at an interim standard.

It was at this point that the 'team', composing of the various organisations including MoD, RAF, BAe and DASA began to work much closer together and found ways to shorten the time scales and get a better standard of software at an earlier stage.

BAe had developed the 'GHOST' development process that allowed modelling and rapid prototyping of systems design algorithms and also cockpit displays. This provided an early assessment opportunity that greatly reduces the possibility of the final design not satisfying the customer's requirement. The new process enabled the RAF project personnel to perform dynamic assessments of the proposed system design and agree what the cockpit displays should look like rather than attempting to specify their requirement on a piece of paper.

The MLU programme involved changing the software, with DASA doing the main computer, BAe the Missile Computer Unit and writing completely new software for the introduction of a Computer Symbol Generator. The traditional method of proving software on Tornado is to undertake sub-system testing, and then to provide a formal release to the full integration rig, which is a representative example of the aircraft on the ground. Once integration testing has completed stringent schedules for flight satisfactorily a formal clearance for flight test is issued. The paperwork formalities took time, and like many other programmes, once the software was released from one stage to the next required improvements would be quickly identified. To overcome this it was agreed to make software-engineering releases available to the integration rig early before the formal paperwork to enable a quick look to enable any obvious improvement requirements to be identified, which could be incorporated before formal release. The process has moved further to allow a number of engineering loads to be progressively released to the next stage so that a higher standard of formal release is achieved. To assist in this process on the integration rig the BAe aircrew would participate in the fitness for flight assessments with the engineering loads so that anything that may compromise a successful flight test could be corrected earlier.

Similarly engineering loads were flight tested where there was no safety critical implications. This shortened the time scales for software development and assisted in achieving an earlier clearance than might otherwise have been achieved. This meant a higher standard of software was available earlier leaving more time to fix any problems and analyse the testing results. Effectively what we did was have a large number of small iterations to the software, 'rolling development' rather than three big loads. The net effect meant that when errors did occur it was easier to identify where they were and hence more easily corrected. All this is an obvious thing to do but changing the attitudes and working practises is always a challenge.

A knock on benefit of using engineering loads is that this method reduces the number of times clearance paperwork was raised. Previously the time consuming paperwork process raised to fly a software load had to be repeated often as the software proved to of limited airborne value. This work was removed, as the software will have been rejected at an earlier point. The downside was additional effort on configuration control.

The process encouraged better teaming and shortened the time from when the software engineers wrote the software to it being tested on a rig. This meant that the software engineers were taking a closer attachment to 'their' work and were disappointed when their work did not work as planned. Hence more pride in their work developed and the association with the aircrew demonstrated how important their input was to the final outcome of the project.

These efforts enabled the development contract to be completed as planned at the end of October 1998. Hence the Production Embodiment programme was not disrupted and the development team was in a position to move forward on the follow-on enhancements to the aircraft.

Production Embodiment

The enormity of the production embodiment task cannot be underestimated. There are over 30 miles of cables in the Tornado aircraft and the MLU programme demanded that most of it be removed with 20% being replaced completely.

Less than two years were available for planning and preparing for the first aircraft on the return-to-works production embodiment programme. The embodiment would take place at the British Aerospace facility at Warton, North West England where the aircraft had originally been assembled. In mid 1995 a 'strategy formulation team' comprising of all the key stakeholders was established to move the planning process forward for the embodiment activities. The team highlighted some of the issues facing the programme as:

- The Logistics system would be the key to the success of the RTW programme. Over 3000 parts and equipment's would be removed from the aircraft and then scrapped, stored for refit or sent away for modification. Further to this over 500 new parts or equipment's had to be fitted to the aircraft. The number of suppliers involved in the supply chain was huge and the management of this process would be critical for the project's success.

- The 'flow' line manufacturing process amplified any problems in the logistics process. Removing parts from multiple aircraft, storing and distributing them centrally, and then trying to control them back to the correct individual aircraft once they had been moved on added further complexity to an already complex system.

- The information technology used by the majority of manufacturing programmes at Warton would not support effectively the complexity which was envisaged on the Tornado MLU programme.

- The manufacturing environment once set up had to be flexible to respond to programme changes and potential future business but it needed to be robust enough to support a seven year activity intensive programme.

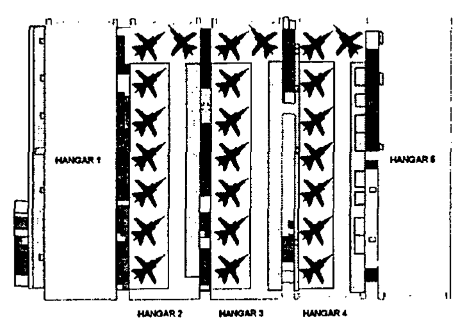

Figure 3 – Aircraft Layout in Hangars

The strategy team developed a network of people from the stakeholders and worked with them to formulate a sub-strategy for each area. Initially the organisation resisted this approach, however over time some key people were able to influence the group and a framework for developing a co-operative working environment ensued.

The strategy team identified five areas of success:
- Process
- Logistics
- Engineering
- People
- Quality

The key decision on the manufacturing process concerned the build philosophy. The team concluded that there should be a complete break from the traditional 'flow' line process and instead each aircraft would remain in a dedicated position, or bay, during its modification and testing. This eradicated the need to move the aircraft during its build and meant that the modification phase, the Production Flight Acceptance Tests and final handover to the customer could be cleared from the same hangar.

The layout of the three hangars allocated two bays at the south end for acceptance of the aircraft on arrival and for engine ground runs / flight preparation at the end of the modification process.

Each dedicated bay has a single parts control area, termed regulators, which act as the focal point for control of all parts taken off the aircraft, stored or transported to a vendor and then replaced on the aircraft. This means it is not possible to mix up parts from different aircraft and secondly parts being 'robbed' from aircraft to satisfy shortages elsewhere can be strictly controlled.

The movement of parts to/from the regulators is achieved by purpose built transportation media. These meet the '*everything has a place*' philosophy ensuring full visibility of complete sets of panels and boxes, and allow the easy identification of missing parts. Alternatively the parts are transported to a dedicated repair and refurbishing area, and then returned to the regulator. Similarly vendor equipment are delivered into the regulator on a strict time scale similar to a 'just-in-time' process.

The normal supply of kit sets of parts to an assembly line is a bag with all the parts tagged to ease their identification by the fitter. On Tornado GR4 the original plan was to adopt best practise in British Aerospace which was on the T45 trainer aircraft assemblies where the parts are delivered nested into foam shadow boards in purpose built suitcases with Perspex tops. However, with a return-to-works build line the required parts for each suitcase would not necessarily be the same, as each aircraft is potentially slightly different. To overcome this a simplified approach has been taken and each kit set is mounted on standard size boards and then vacuum packed, and stored in the regulator.

Once a decision had been made to dedicate bays for each aircraft a number of knock on considerations have to be resolved. In a flow line environment the fitters tend to specialise in one or two phases of a ten phase build process. This leads to some demarcation across individuals, for example, a structure person is prevented from carrying out a mechanical systems test. A team concept is the alternative adopted allowing each operator within the team the opportunity to use his skills in the most beneficial area to the team at any particular time.

One team would manage three aircraft from acceptance to delivery. The main advantage perceived being that ownership would be developed to eradicate some of the problems associated with an aircraft moving down the line often before the work has been completed.

From a purely people point of view it was argued that giving people more options, and more flexibility in the way they worked would create and sustain interest in their working day. If managed properly it would mean that individual skills were being utilised more efficiently for the benefit of the business. By adopting a number of individual teams an element of healthy competition could be evolved between them, for the benefit of the project.

The principle structural changes to the aircraft are restricted to three areas. The most obvious change is on the port underside of the front fuselage where a fairing has been added which houses the new Forward Looking Infra-Red (FLIR) sensor. To accommodate this in the existing structure the left hand gun has been removed and some additional structural strengthening has been undertaken. Another main area is on the lower fin where the Environmental Control System has been modified by using the Tornado ADV primary heat exchanger. The final area are structural changes to the pylons to allow the use of the 1760 weapons databus.

To exacerbate the challenge each aircraft would arrive at Warton at a different standard depending when originally built and whether it was a strike, recce or trainer aircraft. It was recognised at an early stage that the standard of the Tornado's in service varied dramatically and BAe work very closely with the RAF to relieve the situation. The Tornado aircraft come from the operating bases to RAF St Athan for a Pre Input Maintenance Programme, or PIMP. At this point the RAF carry out a major or minor star service, remove any service installed STFs (Special Trial Fits) and check the required modifications on the Minimum Modifications List are fitted. Should any modifications require fitting, or alternatively removing this work is undertaken before the aircraft is flown to Warton to enter the Return-to-Works programme.

The testing of the electrical modifications on the aircraft to identify any wiring anomalies is done before any aircraft equipment is loaded into the structure. This is undertaken by two mobile DITMCo electrical test rigs, which move to each bay when the testing stage is reached in the modification process.

The first aircraft arrived at Warton in April 1996 and was completed twelve months later. The make span is reduced to 8 months by the 17th aircraft delivery. From the end of 1998 onwards 20 aircraft will be in the process of being upgraded until early 2003 when 142 Tornado GR1s will have been upgraded to the Tornado GR4 standard. During this period one aircraft will be returned to the RAF every 8 working days.

The challenge has been met through a combination which started with the extensive forward planning done by the strategy formulation team and moved on with the development of new working methodologies, new equipment, exceptional co-operation with the customer, and tremendous team working arrangements.

The success of meeting the challenge has been achieved by the MLU team questioning our traditional working practices and, where possible, replacing them with innovative ways of carrying out routine tasks and ensuring we continue to improve our methods of working in the most effective manner.

The concepts developed by employee involvement teams prior to the first aircraft arriving at Warton has not stopped. Since the first hangar was completed in early 1996, more than thirty further improvements have been introduced in advance of the two other hangars being completed. Improvement plans and, Customer and employee involvement continue to be a way of life, throughout the GR4 programme, in the drive to reduce costs and meet the Customer's future delivery requirements.

Once work is started on each aircraft some form of emergent work is inevitably found when the aircraft is 'opened up'. This has to be dealt with very quickly, otherwise the delay will have an impact on the planned delivery date which in turn will result in no hangar space being available for the next incoming aircraft. Previously this would have generated a mass of paperwork between BAe and the Ministry of Defence Procurement Executive as the customer, the RAF as the operator, and the relevant design authority for the part of the aircraft affected - Alenia, DASA or BAe. Uniquely representatives from the MoD (PE) and the RAF who between them have the authority to authorise any additional work, and Alenia and DASA personnel are available on site. When problems do arise it is very easy to visit the aircraft and see exactly what is needed, so decisions can be made in a fraction of the previous time. This cuts down on much of the paperwork and reduces delays to a minimum.

Teamwork has been the cornerstone to the Mid Life Update's early successes on the programme and this is not just the customer involvement. Within BAe Integrated Product Teams for development, production embodiment and support have provided the organisational structure in which the total team has focused on the task. On the shop floor, a full support team of planning, design, finance, logistics, and other experts are co-located next to the bays where the aircraft is being worked. This allows the Fitters or Electricians who come across a problem on an aircraft can get an expert opinion straight away. Similarly they can buttonhole the person responsible for giving them an unreasonably difficult task to perform and take them to the aircraft to show them exactly what's what!

Reams of paperwork have also been eliminated by the installation of electronic dedicated Manufacturing and drawing storage and retrieval systems. Terminals are located next to the aircraft so that all those working on them can call up the latest information they need to get on with the job.

Once the aircraft has completed its upgrade to a Tornado GR4 it is delivered to RAF St Athan where a Post Output Maintenance Programme, or POMP, is undertaken. At this point the RAF have the option to embody any Service Embodied Modifications or Special Trial Fits if required. The aircraft are then transferred to their front line operating bases at RAF Bruggen, RAF Marham or RAF Lossiemouth.

The MLU programme is a baseline for further capability growth. These capability enhancements will be introduced progressively as the hardware and software development is completed. The enhancements will be embodied on the Return to Works programme and retro fitted on those aircraft that have already gone through the MLU programme. Hence the planned work content of the RTW programme increases over time, with very little relief on time scales.

Support

Throughout the MLU programme there are a number of innovations that improve processes and on the support aspects of the programme this continues. One of the most important requirements that the RAF desire is the availability of their aircraft when required. The lessons learnt from the experiences gained to date supporting in-service aircraft have been incorporated into the support activities of GR4.

Like the production embodiment contract the support contract with BAe is directly with the Ministry of Defence (Procurement Executive), and is fixed price against a fixed time scale related to the in service requirements. The task covers:

- Initial provisioning
- Aircraft Ground Equipment
- The supply of an avionics ground training rig
- Technical publications
- Training
- Data requirements
- Augmented Logistic Support (ALS)

The most notable innovation is 'Augmented Logistic Support' where the new, high cost, high risk avionics equipment are supported by industry at the aircraft's main operating bases – RAF Bruggen, Lossiemouth and Marham. When an ALS LRU goes defective the RAF collect a replacement from the industry managed ALS store located on the base. The performance requirements are very stringent - 85% of all demands need to be achieved within one hour, 95% within 24 hours and 100% within 28 days.

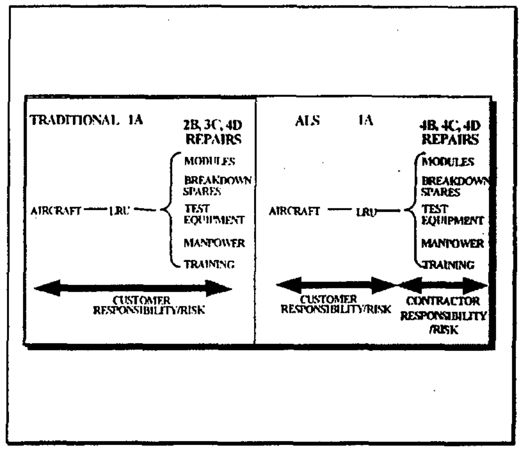

Figure 4 ALS - Change in Philosophy

This support concept provides maintenance on a basis such that industry is responsible for all repairs apart from non-attributable damage. This puts the emphasis on industry to supply reliable equipment in the first place and therefore negates the need for repairs or associated spares. Failure to meet the service level target gives rise to retention penalties so a compromise based upon equipment reliability is determined by industry and not the RAF as previously managed. A slightly different system operates in time of war, when the RAF takes over control.

To date the new process has worked well with minimal difficulties encountered during the introduction into service period.

The Future of the Tornado GR4

The Tornado GR4 MLU programme provides an upgrade in aircraft effectiveness and a baseline for future continuous technology insertion. A parallel life extension programme is on-going to enable the structure and existing equipment in the Tornado GR1 to be qualified to its out of service date around 2020.

As previously stated the MLU programme provides a step change in baseline capability for the Tornado IDS aircraft in the UK. This will make it easier for new more advanced equipment, sensors and weapons to be integrated onto the weapon platform. The speed at which these can be introduced will be determined by our ability to develop new software loads in line with the time scales required to qualify any new hardware.

The RAF wants the most capable aircraft they can get but are restrained by affordability. It would be nice to have a new aircraft but the time scales from inception to in-service are now in the order of 20 years and the funding required is enormous, notwithstanding the political challenge and will. Therefore in the short to medium term the only option to improving the aircraft's capability is an upgrade, and that only happens if the funds can be justified against other competing demands. The RAF has four requirements:

1 Mission success. - There is no point sending highly trained men on a mission if it is unlikely to be successful.

2. Effectiveness. There is no point sending highly trained men on a mission using equipment that is no longer effective for its planned task.

3 A consistent standard of aircraft. With the same standard of aircraft fleet management is minimal. Availability of specific aircraft due to their 'special' equipment fitted and the subsequent specific support add significantly to the fleet management task.

4 Avoid red line entries. It is no good having highly capable aircraft if they are grounded due to a shortage of spare parts.

So, what can and cannot be done economically to an aircraft? Our experience on Tornado tells us that as long as the aircraft can remain effective and successful in its missions then it will generally make economic sense to upgrade. There are likely to be fewer advances in airframe design compared to the advances possible in systems over the coming years. Within BAe we view the aircraft as the platform for the weapon systems and therefore it is important to get the system flexible enough to integrate updated and improved systems onto the existing airframe. It is only when the fatigue life of the airframe makes it too costly to upgrade to be safe to fly that a new aircraft is justified. During this period undoubtedly new ways and methods of doing things may not be economically feasible on an existing airframe, for instance smart skins. Progressively the aircraft will lose capability in comparison to newer aircraft available on the world stage, and at some point its effectiveness and ability to achieve mission success will be sufficiently compromised to justify the development of a new weapon platform.

This view is sound in an environment where there is no longer a serious threat. The situation may be different in an arms race where a greater proportion of the nation's GDP would be directed towards the Defence budget. Once a decision is made to go for a new aircraft the new air platform should provide a step change in performance.

The limitations to extending the useful life of the aircraft will heavily depend on the RAF's four requirements. Clearly if any of these are compromised it would not be in the UK's interest to continue extending the life of the aircraft. From a Design Authority's viewpoint maintaining the safety of the aircraft is of paramount importance. As the aircraft ages overcoming obsolescent equipment and ensuring the structure has clearance qualifications for the platform's extended life are serious considerations. Similarly from an operator's view the cost of maintaining an ageing aircraft will eventually become unacceptable.

The approach taken for Tornado GR4 to integrate new technology advances has been to provide a versatile design. The MLU programme restructured the original design to make the aircraft's avionics systems more versatile and capable of upgrading. Significant upgrades will come with the introduction of the various Packages planned. There must be a limit on what can be integrated onto the GR4 system but as yet that limit has not been reached.

Current Programme Status

The initial phase of the MLU Development programme was successfully completed in September 1998, and the Production Embodiment programme is now at full speed. The follow on packages are now defined. Package 1 will be embodied next year; Package 2 development activities are underway and the contents of Package 3 and 4 are now defined. There is no doubt that the Tornado GR4 has given the Royal Air Force a significant improvement in capability and the currently planned Package improvements will ensure the Tornado remains an effective strike aircraft well into the 21st century.

MIRAGE 2000 COMBAT AIRCRAFT UPGRADE IN DASSAULT AVIATION

Solution for NWDS System open and affordable

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MIRAGE 2000 are in operational service within several Air Forces since 1983. The outstanding structural sturdiness of the Mirage allowing them to fly over 2015-2020, allow Dassault Aviation to consider mid-life update.

MIRAGE 2000 mid-life update shall comply with the following criteria :

- Multirole aircraft, able to carry a wide variety of Air to Air and Air to Surface missions,
- Affordable costs,
- Replacement of current sensors (for example : RDM radar) by state of the art modern sensors with up to date operational performances (for example : multi shoot fire control),
- Replacement of the current WNDS core system by an open system based on modular avionics architecture allowing, in particular, to separate application software and hardware,
- Replacement of the current cockpit lay out by a modern glass cockpit taking benefit of the numerous advantages of the Man - Machine - Interface fitted on the MIRAGE 2000-5,
- Implementation of new functions, by the customer's national industry, thanks to a modern software workshop installed at the customer's facilities.

The target of this mid-life update is to obtain a new version of MIRAGE 2000 with a fly away price for new aircraft of 80% of the one of MIRAGE 2000-5 but with attractive operational characteristics.

1. CHOICE OF OPERATIONAL FUNCTIONS

Marketing approach followed in the market of new modern aircrafts, or updated versions of existing airframes, indicates that operational potentials of these airplanes are high.

In this context Dassault Aviation has decided :

- To fit the basic version of the future MIRAGE 2000 with :
  - an air to ground firing control with standard bombs, guns and rockets,
  - an air to air firing control with IR combat missile.
- To size the complete system to be able to add options on customer's request without modification of the core system :
  - Air to Air mode : BVR missiles with at least double shoots fire control.
  - Laser Guided weaponry
  - Data link
  - etc...

Dealing with updated versions, the basic solution has to be tailored to fit the customers' specific needs ; three levels of upgrades have been identified :

- Level 1 : full mission system upgrade.
- Level 2 : the existing system is maintained in the present state, new functions and new equipments are integrated into an additional core system.

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

- Level 3 : new functions and new equipment are integrated in the existing system with minor modifications.

Level 2 and level 3 upgrades are made up level 1 subsets.

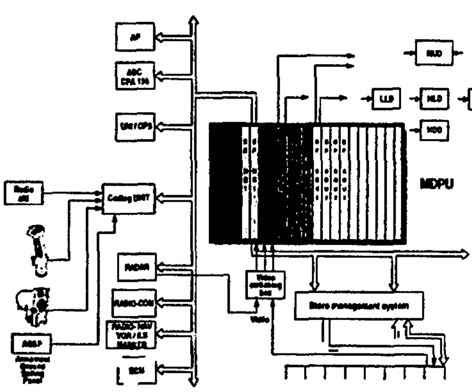
2. TECHNICAL DEFINITION OF THE WNDS

Technical definition of the airframe, engine and weapon system was reviewed in order to find a compromise between cost and efficiency, while reducing impacts on recurring and no recurring costs :

- by simplifying actual functions (reduction of number of components)
- by using already engaged developments, showing cost reduction potentialities
- by using dual new technologies, decreasing the cost and able to cope with obsolescence problems.

2.1 - Architecture

The effort on cost reduction is mainly visible on the weapon system. A new architecture of data processing, developed around a core system with modular avionics, provides a significant reduction of development cycle and offers to the customer a potentially more evolutive system with growable capabilities, as shown below.



2.2 - Core System

The targets of the avionics core system new approach are :

- to reduce development cycles and recurring cost of the WNDS
- to have an important growth capability of the core system.
- to have a better obsolescence management and best use of current technology at any time,
- to be able to reuse already developed software with no regression.

This approach is based on :

- a standardised core data processing, the Modular Data Processing Unit (MDPU : Dassault Aviation - Dassault Electronique - Sextant),
- a new system and software environment based on an objet oriented system workshop (ODILE)
- an encapsulation of existing software with adequate interfacing with new software.

2.2.1 - MDPU generic architecture

In order to meet the important growth capability objective assigned to the new core system, the proposed core data processing has been conceived as a modular, scalable, open and evolutive platform (see fig. below) : inside a rack, power supply function and standard functional modules (up to 18) communicate through a backplane. The standard functional modules are :

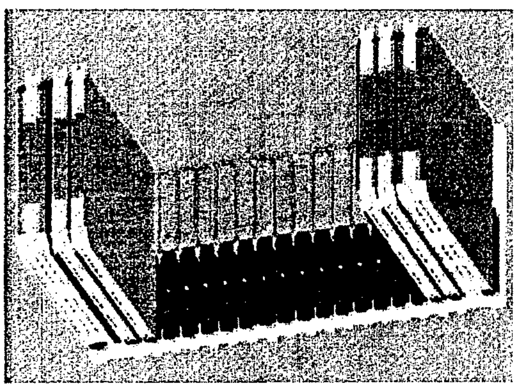
- a Data Processing module (DP)
- a Graphic Processing module (GP)
- a Mass Memory module (MM)
- a Bus Coupler module (BC)

Each of the standard modules has been designed making the best use of COTS and current technology. As an example, the new processing power of one Data Processing module is 50 times higher than the one of the present M.2000 Mission Computer.

The obsolescence management has been taken into account by using standard interfaces between the various components of the MDPU in order to be able to change hardware and software components without any impact on the application software. Furtherone, this makes the associated evolutions easier by allowing a component to be changed with minimum impact on its environment. The standard interfaces concern the hardware as well as the middleware components. The Operating Software can be changed without any modification of the application software. In the same way, the CPU of the Data Processing module can be changed independently of the others functions implemented in the module.

The modular configuration of the MDPU also contributes to simplify maintenance procedures, the LRU concept being replaced by a LRM concept.

This core system will be installed on all present Dassault Miltary programmes (M.2000-9, Rafale, ATL3).



2.2.2 - *MIRAGE 2000 Configuration*

The proposed configuration for the MIRAGE 2000 includes the functions implemented in the two Mission Computers and the two Symbol Generator Units in the previous architecture : mission management including operational moding management, display and control management, maintenance management. The Data Processing Module containing mission computer software is totally redundant so that then one fails, all the operational capabilities are kept (no degradation in back up mode).

2.3 - Radar

2.3.1 - The basic radar is the Thomson-CSF RC 400, with an emitting power of 400 W, allowing a firing capability of two simultaneous targets in Air to Air mode, with a range slightly lower than the one of RDY radar. Signal processing functions are directly derived from the algorithms of the RDY, and therefore must provide a very similar quality and sturdiness of the fire control, but with a significant price reduction.

This radar is presently under development.

2.3.2 - The multitarget RDY, radar of the M.2000-5/-9 is obviously available upon customer's requirement.

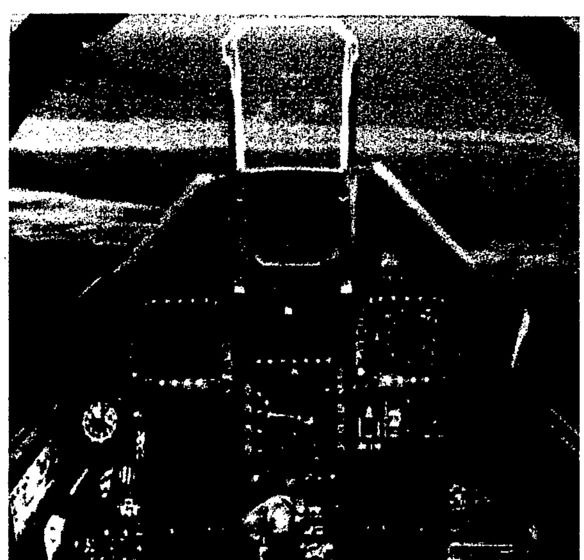
2.4 - Cockpit lay out

In service experience has shown that the M.2000-5 cockpit concept with five displays was very much appreciated by combat pilots.

This is mainly due to :

- the concept Head up - Head level displays collimated at infinity, giving without accommodation by pilot's eye both the immediate situation (HUD) and the main sensor display,
- a peculiar display dedicated to the long term, ie tactical situation (HDD)
- two interactive lateral displays and a mode selector panel, last three displays will be LCD.

It was stated that such a cockpit gives to the pilot a good and clear situation awareness, even in heavy workload phases.



2.5 - Others functions

- The inertial platform is a Sextant TOTEM 3000 Gyrolaser with GPS hybridisation.
- The radiocom system could be provided by the customer national industry as the ECM and Stores Management Systems.

3. CUSTOMER'S ON SITE DEVELOPMENT ENVIRONMENT : ODILE

- The objectives of the on site environment are mainly to give to the customer the ability to modify the MDPU software which has been initially developed by French Industry : same environment based on ODILE is used in France to develop oriented objet part of software functions. This is provided in order to :

- give to the customer ability to make system level modifications (by opposition to going directly at very detailed local software level),
- with the shortest modification cycle : ability to show prototyped functions to pilots and to complete development and validation up to flight test in short time,
- so that the modification has no impact on the existing object oriented and encapsulated part of the software. No regression test on this part is necessary after reuse of already developed software.

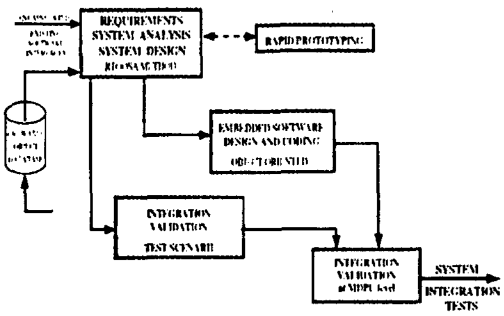
This workshop incorporates some new tools and relies on the same new methodology (Dassault Aviation System Development Methodology - DSDM - based on RTOOSA) as those used in France by Dassault Aviation to develop software in object oriented technology for new functions.

It is composed of :

- an OASIS rapid prototyping facility for pilot in the loop Man Machine Interface (MMI) simulation
- a DSDM development environment with :
  - Δ analysis tool-sets for system requirements analysis
  - Δ system design tool set
  - Δ software development tool set for software design, coding and testing
- a MDPU Hybrid Simulator for integration (validation of MDPU software)

This workshop will be supplied with appropriate training and assistance.

The development process is described in figure below.



Aircraft Life Extension - CC130 Hercules Avionics Update

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1. Summary

The Canadian Department of National Defence (DND), having taken measures to ensure the structural integrity of the CC130 Hercules to beyond 2010, studied a number of technical and economic options with respect to extending the life of its ageing CC130 Hercules avionics suite. The Department selected the option of a consolidated and comprehensive avionics update as the preferred option to ensure the aircraft can perform its missions with peak efficiency and that the avionics would meet or outlast the estimated life expectancy for the aircraft.

2. CC130 Estimated Life Expectancy

The structural life of the aircraft was not established at the time of design. The Canadian Department of National Defence (DND) has completed progressive wing replacement programs, and maintains ongoing Durability and Damage Tolerance Analyses, Aircraft Structural Integrity Program (ASIP), Progressive Structural Inspections (PSI), and Aircraft Sampling Inspections (ASI). Most recently, the DND has implemented a usage monitoring and fleet management program through installation of on-board data recording systems on the CC130 fleet. These systems will record actual load data, which can then be related to the specific flight profiles. In turn, fleet-wide usage and severity can be assessed, based on knowledge of the missions flown and the actual loads experienced during each mission.

Collectively these efforts aided in extending the estimated life expectancy (ELE) of the DND CC130 fleet to 2010.

3. Introduction - Avionics Update

The CC130 fleet is composed of six distinct Hercules models, each equipped with a different avionics configuration. These avionics variations ranged in nature from minor to significant and hinder flight crews from maintaining operational proficiency on all CC130 models. This imposed restraints on full-fleet utilisation during periods of maximum airlift requirement. Additionally, the majority of the aircraft in the fleet were fitted with certain avionics that would become obsolete and/or unsupportable prior to the ELE of 2010. In order for the CC130 to achieve its (structural) ELE of 2010 it was deemed necessary to replace or upgrade the fleet's avionics systems that could soon become unsupportable and/or not meet new international communication and navigation standards.

At the time of project initiation, over half of the DND CC130 fleet were 20-30 years old, with approximately 35000 flying hours. Notwithstanding their average age, the expense of replacing the fleet prior to the ELE of 2010 was discounted as a cost-effective means of resolving the avionics deficiencies and life-cycle shortfalls. It was considered essential from an operational and economic standpoint that all CC130 Hercules aircraft receive a standard and updated avionics suite.

Thus, to ensure that the CC130 continued to be an effective airlift resource until an ELE of 2010, these specific deficiencies were cited for resolution:

- the layout and type of flight-critical instrumentation is not standardized within the fleet, requiring specialized aircrew currencies to fly the various CC130 configurations;

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

- current avionics systems will not meet the increasing navigation, communications, and identification requirements for the fleet's Strategic airlift, Search and Rescue (SAR), Tactical Air Transport (TAT), and Air-to-Air Refuelling (AAR) missions;
- a number of avionics systems, including the compass, the autopilot, the flight director, the doppler, and the communications suite, are unreliable, difficult to support, and in some cases no longer meet Regulatory and operational requirements;
- other systems, such as the radar display, are unreliable and difficult to support, despite being operationally suitable; and
- new systems such as Ground Collision Avoidance System (GCAS) enhance flight safety, and conform to new commercial regulatory requirements.

4. Option Analyses

4.1. Avionics Requirements Document

An Avionics Requirements Document[1] was developed to detail the requirements for the standard cockpit instrumentation and avionics suite. These requirements were based upon existing and documented operational CC130 missions and roles.

To document the derivation of the requirements for the standard avionics suite, an Avionics Mission Roles Analysis was conducted based on a top down analysis of the CC130 missions (strategic airlift, SAR, TAT, and AAR). An essential characteristic of all missions was worldwide, all weather, Category II Approach conditions. The missions were divided into individual segments, such as take-off, cruise, payload delivery, and approach. Each mission segment was then subjected to a detailed analysis to establish its requirements for the cockpit instrumentation and avionics systems.

Each mission segment underwent a detailed review relative existing specifications, standards, and regulatory requirements for these flight segments. Due to the integrated nature of civilian and military air operations, civilian specifications, standards and regulations were given equal consideration relative their military counterparts. Further, Canada is a signatory to many NATO standardization agreements (STANAGS) which directly relate to CC130 Hercules avionics requirements. The Avionics Requirements Document, and its Avionics Mission Roles Analysis, considered all of these requirements in detailing avionics requirements.

The results of the Avionics Mission Roles Analysis were collated and assigned to systems in six functional areas: navigation, communication, identification, flight control/guidance, on board systems, and self-protection. The most demanding requirements within each functional area were identified and associated with their supporting reference.

The Figure 1 illustrates the segmented, graphical nature in which avionics requirements were identified (navigation for strategic missions). Figure 2 depicts an example of the results for navigation (all missions).

4.2. Standard Avionics Specification

A Standard Avionics Specification[2] was then developed to detail the recommended standard avionics configuration for the DND CC130 fleet. It also initiated an economic analysis through calculation of rough order of magnitude procurement and installation costs for the implementation of the Avionics Requirement Document recommended avionics suite.

The avionics systems installed or planned for installation in DND CC130 Hercules, other DND aircraft, Lockheed production aircraft, and United States Air Force baseline Hercules aircraft, were researched and evaluated in terms of the identified avionics requirements and their supportability through to the ELE of 2010. Those systems, which were supportable and met appropriate avionics requirements, were recommended as candidates for the CC130 avionics update. These candidate systems were then synthesized into system options and traded-off in terms of technical and cost elements. Based upon the results of this trade-off, the recommended standard avionics configuration was specified.

To ensure an objective evaluation of avionics requirements and supportability, each of the systems options were evaluated by development of an evaluation methodology based upon two summary evaluation factors; a technical figure of merit (TFOM) and a cost figure. When these two factors had been rated for each option, a recommendation as to the preferred option was identified.

Technical Figure of Merit. The TFOM was subdivided into evaluation elements, with each element mutually exclusive, and definable. An appropriate weighting factor was assigned to each element based on a direct estimation of the relative element priority. An assigned score of one to five was then multiplied by the weighting factor for that element, and "rolled-up" to provide an overall TFOM score. Evaluation elements and weightings were:

- **Capability** - the extent to which the system meets the requirements of the Avionics Requirements Document. Weighting 25;
- **Supportability** - the relative probability that the system will be economically supportable to the ELE of 2010. Weighting 25;
- **Availability** - relative reliability and maintainability of the system. Weighting 10;
- **Growth**; relative growth capability in terms of interface options, throughput and memory expansion. Also considered was the degree to which the system could be adapted to other aircraft within the DND. Weighting 5;
- **Commonality** - relative impact upon the DND Logistics System (training, publications, spares, test equipment). Weighting 15;
- **Risk** - relative risk of system development and integration for the CC130 Hercules application. Weighting 20;

Cost. For the summary cost factor, each of the following relevant cost elements were identified (Figure 3):

- **Fleet Equipment Cost** - the hardware and software costs to fit the Hercules fleet;
- **Non-Recurring Engineering (NRE) Cost** - the sum of one-time costs incurred in adapting the system hardware and software to the Hercules suite, and completion of installation design and prototyping. A factor of between 2 and 10 times the per aircraft installation costs was assigned;
- **Test & Support Equipment Costs** - test & support equipment costs for 1st (Organizational) and 2nd (Intermediate) level maintenance;
- **Initial Spares Costs** - in the absence of specific sparing recommendations, a value of 25% of fleet cost was assigned and 22% for dual installations;
- **Documentation Costs** - unilingual operations and maintenance documentation;
- **Training Costs** - initial operations and maintenance personnel training (exclusive of flight simulator modifications).

The result of the Standard Avionics Specification work was the identification of the preferred system, technically and financially, for each of the Avionics Requirements Document requirements (ie TACAN, VOR/ILS, VHF, UHF,...). The economic analyses performed through this Standard Avionics Specification work resulted in a rough order estimate of $90M (1989/1990 Canadian dollars) for the upgrade of the DND CC130 fleet. Lastly, the Standard Avionics Specification work concluded with the identification of future developments at Lockheed and within the United States Air Force which could impact upon the recommended avionics configuration (EFIS, FMS, and digital flight control system) and merit future consideration.

4.3. Avionics Update Development Study

A CC130 Avionics Update Development Study[3] was then completed, in consideration of the Standard Avionics Specification recommended systems, to compare and present the three preferred suite options for proceeding with a CC130 avionics update.

Since there were a significant number of individual avionics subsystems to be replaced, it would have been possible to identify innumerable options, differing only in the particular equipment proposed. The Avionics Update Development Study presented three broad options; these were:

- **Piecemeal approach** - whereby individual projects would be used as the vehicle for addressing both operational and maintenance requirements. Under this scenario, avionic equipment requirements would be addressed by individually staffed and managed stand-alone projects;

- **Lockheed standard** (Model 382C-63E) - At the time, this option reflected the configuration of the DND's latest CC130 aircraft, and would consist primarily of changing the older E and H Models to this avionics and cockpit configuration; or

- **CF baseline standard** - whereby all of the preferred avionic systems of the Standard Avionics Specification would be used, reflecting an operationally acceptable, cost-effective solution.

Analysis of the Options. Detailed analyses of the costs and performance capabilities of the options were conducted and were summarized within the Avionics Development Study. The piecemeal option would too slowly, if at all, resolve the critical problems, which gave rise to the project (Section 3. above). The two remaining options were determined to be essentially identical in their projected costs, however, the CF baseline standard was determined to:

- provide navigation and communication systems which will better meet new international standards;
- allow for future growth via an Interface Computer Unit (mixed data busses);
- incorporate newer systems which have higher Mean Time Between Failure (MTBF), resulting in improved serviceability;
- can also be implemented using currently available, off-the-shelf subsystems;
- provide greater reductions in 2nd (Intermediate) and 3rd (Depot) level maintenance support; and
- provide for substantially larger 1st level (Organizational) maintenance personnel savings.

The CF baseline standard was selected and approved as the recommended option.

5. Contract Development

5.1. Prime Item Development Specification

A Prime Item Development Specification was then developed from the Standard Avionics Specification to contractually describe the functional and regulatory requirements for the avionics suite. Through a period of almost two years, including a formal Request For Proposal phase, input from Industry was sought to best ensure that the resultant contract, and particularly the Prime Item Development Specification, would promote a successful, risk reduced, and cost efficient implementation. Notwithstanding this level of preparation, both the DND and the Prime Contractor continued to extensively amend the Prime Item Development Specification throughout the first year's conceptual and preliminary design phases; seeking further improvements, risk reductions and cost efficiencies.

5.2. Contract Award

After more than a year's liaison and negotiation with Industry, the CC130 AUP contract was awarded. The accuracy of the Standard Avionics Specification economic analysis' cost estimates proved sound as the prime contract award value was within the (upper) error estimate.

5.3. Modification Development

The development of the DND CC130 Hercules AUP modification closely followed the MIL-STD-1521 Systems Engineering process. In view of the extent of required integration and software development, a Hot-Bench was manufactured and populated with all systems for the purpose of supporting these risk-inherent activities. In addition, the front section of a C130 Hercules (Flight Station 270 and forward) was acquired and also populated with all AUP systems to support design, development (particularly maintainability and Human Factors engineering), testing and initial training. Thirty-nine months were required from contract award through to prototype acceptance.

5.4. **Completed Modification**

The resultant DND CC130 Hercules AUP modification resulted in the following equipment installations:

- Aircraft Flight Control & Display System (civil):
  - Electronic Flight Instruments (Cathode Ray Tube),
  - Air Data sub-system,
  - Attitude and Heading Reference sub-system,
  - Autopilot sub-system,
  - Standby Instruments.
- Flight Management System (military):
  - Control Display Units,
  - Bus System Interface Units,
  - Remote (heads-up) Readout Units,
  - Emergency Control Panel,
  - Data Transfer sub-system (ARINC 424 data, etc).
- Display and Instruments System (military):
  - Navigation Data Display sub-system (radar display),
  - Ground Collision Avoidance sub-system.
- Self-Protection System (installed previous to the AUP):
  - Radar Warning Receiver sub-system,
  - Missile Approach Warning sub-system,
  - Countermeasures Dispensing sub-system,
- Navigation System (military/civil mixture):
  - Global Positioning sub-system,
  - Inertial Navigational Units,
  - VOR/ILS and Marker Beacon sub-system,
  - Automatic Direction Finder sub-system,
  - Identification Friend or Foe sub-system,
  - Distance Measuring Equipment sub-system,
  - Radar Altimeter sub-system,
  - Air Traffic Control Radio Beacon sub-system,
  - Multiband Direction Finder sub-system (distress frequencies),
  - TACAN sub-system,
  - VHF Direction Finder sub-system (distress frequencies).
- Communications System (military):
  - High Frequency sub-systems,
  - Combined Very High & Ultra High Frequency communication sub-systems,
  - Stand-alone Ultra High Frequency sub-system,
  - Secure Voice sub-systems,
- Recording System (civil):
  - On-Board Loads Monitoring sub-system,
  - Solid State Flight Data Recorder sub-system,
  - Solid State Cockpit Voice Recorder sub-system.
- Data Bus System (military/civil mixture):
  - MIL-STD-1553B sub-system,
  - all other data buses (ARINC, CSDB).

Through these extensive system installations, the project succeeded in the resolution of the original deficiencies that prompted the project:

- the layout and type of flight-critical instrumentation has been standardized for all models of Hercules within the fleet, greatly reducing any specialized aircrew currencies to fly the various CC130 aircraft;
- mission deficient systems have been replaced with new avionics capable of present and foreseen navigation, communications, and identification requirements for the aircraft's missions and roles;
- all systems which were not supportable to the ELE of 2010 have been replaced;
- all but one of the top ten maintenance intensive avionics systems were replaced with new systems with 10 times better

reliability (economic analyses of the one exception (radar) did not support replacement).

6. Aircraft Update - The Economical Alternative?

6.1. What Can and Cannot be Done Economically?

In a manner analogous to aircraft maintenance analyses, as conducted through the Maintenance Steering Group - 3 (MSG-3) logic within the DND, one must first determine which aircraft deficiencies are sufficiently critical that they require upgrades or replacements independent of economic factors. Of the remainder, where one has an option of continuing with the status quo, an economic study analogous to a Logistics Support Analysis (LSA) Level of Repair Analysis (LORA) is best conducted. Such a study will trade-off the increasing costs of the status quo, against the projected capital costs of upgrading/replacing and the anticipated future (reduction) of in-service operations and maintenance costs.

The DND CC130 AUP analyses in fact produced several cost/benefit results, which did not support upgrading, or replacement. Notably, the APN-59E radar is the most maintenance intensive avionic system on the CC130 aircraft. However, the radar meets all operational requirements and the cost to upgrade or replace the radar, even with projected maintenance/in-service cost savings, would not likely "pay-off" prior to the ELE.

Essentially, the Standard Avionics Specification and Avionics Development Study identified both the obligatory (operational and regulatory) requirements for the update, and further update recommendations where technical and economic analyses supported such changes.

6.2. What Are the Limitations to Extending the Useful Life of Aircraft?

Life extension of aircraft is ultimately a least common denomination function. Engineering and Maintenance seek the resources to push the lowest common denominator safely out to the calendar's right. This is, however, subject to the law of diminishing returns. Ultimately the year-over-year costs and marginal benefits of working to further extend the life of aircraft will not exceed the amortized costs and benefits of working to replace the aircraft. In this sense, aircraft systems may be the least common denominator precluding the cost-effective implementation of structural upgrades, or vice versa. For the DND CC130 AUP (circa 1990), the avionics were the least common denominator. As a result a cost-effective upgrade was identified and implemented to align the "life" of the avionics to the estimated life of the structure and remaining aircraft systems.

6.3. How Can Technological Advances Be Integrated?

Military procurements continue to evolve to commercial-off-the-shelf (COTS) products, which are increasingly driven by commercial specifications and standards[4]. These COTS products are subject to shorter, more rapid life cycles than their military predecessors[5]. Militaries are faced with early lifetime buys of systems and spares, or must plan to soon integrate upgrades and/or replacements.

Adding to this quickening evolution, are Regulatory changes, such as Traffic Collision Avoidance Systems, Ground Proximity Warning Systems, 8.33 MHz Channel spacing, Mode S transponders, Area Navigation, and GPS Receiver Autonomous Integrity Monitoring. The rapid technological advances of the computing and telecommunications industries are inducing derivative changes to the aerospace environment.

Shortened life cycles are making the requirement to add technological advances to not only in-service aircraft, but midstream within a Project, increasingly difficult to avoid. Apparent through the study of DND Capital acquisition projects, non-military, and international projects (F-16, USN Guided Missile Frigate, Oil Sands Extraction and Chemical Processing plants), is that average elapsed time for such projects is surprisingly similar: around 120 months. More over, the elapsed time appears independent of the physical size of the end product, or even the nature of the project.[6] It was found that a project's duration is determined essentially by its complexity as measured by the degree of systems integration and by the degree of its physical and data-exchange linkages to other existing systems; production is typically the easiest phase. These time lines make it very probable to have to entertain design changes to include/integrate the latest technical advances. To reduce the potential design change complexity, plan on the likely systems integration and data-exchange linkages.

Avionics designs should be developed with the expectation to include and reserve space for such future additions. Thought must be given to:

- preferred, reserved, electromagnetically compatible antenna locations,
- interface computers capable of integrating both military and civil data bus standards,
- reserved avionics bay locations which maximize maintainability and reliability,
- electrical system capacity and spare components (circuit breaker locations, junction box access),
- procure systems which are likely to evolve in a form, fit, function manner for foreseen upgrades (GPS for RAIM/WAAS/LAAS),
- implement Logistic Support and Configuration Management processes that can easily adapt to upgrades and replacements.

7. Conclusion

In the early 1990's the Canadian Department of National Defence resolved that the CC130 Hercules avionics systems would limit the ability of the fleet to attain an ELE of 2010. Through a systematic process of technical and economic analyses, an Avionics Update Project was developed and approved to replace or upgrade a large proportion of the cockpit avionics. Though AUP modified aircraft have yet to complete a full year of in-service operations, capital expenditures and in-service logistics data thus far support the economic merit of updating avionics for mid-to-long term resource savings and aircraft life extension.

1 Electronic Warfare Associates - Canada, Ltd. **Avionics Requirements Document**, Prepared for the Department of National Defence, Contract W8465-8-AMNN/02-BQ, 30 November 1989

2 Electronic Warfare Associates - Canada, Ltd. **Standard Avionics Specification**, Prepared for the Department of National Defence, Contract W8465-8-AMNN/02-BQ, 20 August 1990

3 Department of National Defence, Report 32370-100-008 **Avionics Update Development Study**, 25 November 1991

4 Matthews, J. and Condra, L., **Avionics Magazine**, March 1999, "The Growing Problem of Component Obsolescence"

5 Sweetman, B. and Cook, N., **INTERAVIA**, January 1999, "Military Avionics: engine of change or obsolete relic?"

6 McFarlane, G., MGen (retd), Letter to Chief of the Air Staff, November 13, 1998

HIERARCHY OF FUNCTIONAL REQUIREMENTS (FOR STRATEGIC AIRLIFT)					REGULATION OR REQUIREMENT
AA - Strategic Airlift/Standard	AAA - Navigation	AAAA - IFR	AAAAA - Reqr ADF or VOR or TACAN		CFP 100(1), Chap 5, Para 6
			AAAAB - Nav without Ref to Earth/Water		CFP 100(1), Chap 5, Para 6
		AAAB - Nav System Requirements	AAABA - Display/Control	AAABA - Avail Pilot/Co-Pilot/Nav Stns	DAR 3-5, 11500LT-1
				AAABAB - Position of Pilot Operatied	NATO STANAG 3258
				AAABAC - Minimum Quantity	DAR 3-5, 11500 LT-1
			AAABB - Appropriate for ATC Req't		ICAO Annex 6, Part 1, 7.2.1
			AAABC - ADF System Characteristics		ICAO Annex 10(1), Part 1, 3.9
			AAABD - DME System Characteristics		ICAO Annex 10(1), Part 1, 3.5.
			AAABE - VOR	AAABEA - System Characteristics	ICAO Annex 10(1), Part I, Att C
				AAABEB - Interference Immunity	ICAO Annex 10(1), Part 1, 3.3.8
			AAABF - ILS	AAABFA - System Characteristics	ICAO Annex 10(1), Part I, Att C
				AAABFB - Interference Immunity	ICAO Annex 10(1), Part 1, 3.1.4
			AAABG - TACAN System Charateristics		NATO STANAG 5034
			AAABH - True/Mag/Grid Nav Capability		DAR 3-5, 11500LT-1
			AAABJ - Redundancy		DAR 3-5, 11500LT-1
					ICAO Annex 6, Part 1, 7.2
			AAABK - Integration	AAABKA - Requirement	DAR 3-5, 11500LT-1
				AAABKB - Sensor Reinitialization In-flight	DAR 3-5, 11500LT-1
			AAABL - One Self-Contained Nav Sys		DAR 3-5, 11500LT-1
			AAABM - Operate at LAT up to 82 Deg N		DAR 3-5, 11500LT-1
			AAABN - Operate at Temps to -50C		DAR 3-5, 11500LT-1
			AAABP - Max 20 Min Until Full Nav Capability		DAR 3-5, 11500LT-1

FIGURE 1

CC130 Avionics Update - Life Extension

NAVIGATION SYSTEM REQUIREMENTS	REQUIREMENT
VOR Receivers	2
ADF Receivers	2
TACAN Receiver (Includes DME Capability)	X
Air-to-Air TACAN Station Capability	X (KC130 Only)
Radar for Weather Avoidance, Ground Mapping, and Formation Station Keeping	X
ILS Glideslope and Localizer Receivers	2
Radar Altimeter	X
Cockpit Display of Drift and Ground Speed	X
Marker Beacon Receiver	X
Horizontal Position Accuracy (2 drms)	+/- 50 Meters
Altitude Accuracy (AGL, 2 sigma, below 800 Feet)	+/- 10 Feet
One Self-Contained Navigation System	X
Minimum Navigation Performance Specifications Certified	X
Wind Speed and Direction at Aircraft Altitude	X
Pattern Flight Navigation Capability	X
Emergency Frequency Direction Finding Capability	X
Integrated Navigation System	X
True/Magnetic/Grid Navigation Capability	X
Displays and Controls Available at Pilot, Co-Pilot and Navigator Stations	X
Capable of Operating at 82 Degrees North Latitude	X
Maximum 20 minutes from Aircraft Power Application Until Full Navigation Capability	X
Capable of Operating With Ramp Temperatures to -50 Degrees Celsius	X
Continuous Indication of Track Position to Flight Crew	X
Global Positioning System Receiver	Future
Microwave Landing System Receiver	Future

FIGURE 2

CC130 Avionics Update - Life Extension

SYSTEM: ARN-127 VOR/ILS/MB System

COST DATA SOURCE: DND

COMMENTS: It is assumed that the existing antenna would be used.

FLEET EQUIPMENT COST: $303,,300

Item	Quantity per System	Cost (each)	Total Cost
Receiver	1	$13,300	$13,300
Control	1	$3,000	$3,000
Mount	1	$550	$550
			$16,850

	CC1130 Aircraft Model				
	E	H	H(73)	H(84)	H(89)
System Quantity Currently Installed	2	2	0	0	0

Fleet Equipment Cost = System Cost x Quantity per Aircraft x Number of CC130 AC to be fitted
= $16,850 x 2 x 9
= #303,300

FLEET STAND-ALONE INSTALLATION COST: $421,875

Fleet Stand-Alone Installation Cost = Installation Man-hours x labour Rate x Quantity per Aircraft x Installation Kit Multiplication Factor x Number of CC130 AC to be fitted
= 250 x $75 x 2 x 1.25 x 9
= $421,875

NON-RECURRING ENGINEERING (NRE) COST: $93,750

Estimated to be 2 times the installation cost for one aircraft, as already installed in the majority of CF Hercules fleet. Equates to 2 x $46,875, or $93, 750.

TEST & SUPPORT EQUIPMENT COST: $0

Nil, existing CF support equipment sufficient

INITIAL SPARE S COST: $66,726

Initial Spares Cost = 22% x Fleet Equipment Cost
= 0.22 x $303,300
= $66,726

DOCUMENTATION COST: $0

Nil, already in CF inventory and installed in CF Hercules aircraft.

TRAINING COST: $0

Nil, already in CF inventory and installed in CF Hercules aircraft

TOTAL PROCUREMENT COST (sum of above costs): $885,651

FIGURE 3

CC130 Avionics Update - Life Extension

CC130 Problem Systems

Function	System (Note 1)	Maint Hrs /1000 Flt Hrs (Note 2)	MTBF Hrs (Note 2)	Ops Effect % (Note 3)	In Production	Support to 2010 (Note 4)
Radar	APN-59F	314	56	17	No	Low
Recorder	USH-502(V)1	251	69	4	No	Low
DVS	APN-501A	179	98	3	No	Low
Autopilot	E-4	119	112	4	No	Low
Compass	C-12	97	109	12	Yes	High
Rad Alt	APN-150	91	306	1	No	Low
Nav Computer	ASN-504	80	115	4	No	Low
IFF	APX-77	79	158	9	No	Low
Nav Computer	AYN-501	75	129	1	No	Low
Omega	ARN-509	57	264	3	No	Low
Flt Director	MA-1	53	112	28	No	Low
ADF	ARN-6	48	293	1	No	Low
Comm HF	ARC-505	46	327	3	No	Low
Rad Alt	APN-133	34	434	0	No	Low
Astral Compass	SAC	28	390	4	No	
TACAN	ARN-504	28	555	1	No	Low
UHF DF	ARA-25/50	10	2100	0	No	Low

Notes:

1. Systems shown if MTBF is less than 400 hours or there is a low probability of support to the year 2010.

2. Figures based on Aircraft Maintenance Management Information System data. Equipment installed on only a few aircraft is not included because of small sample size.

3. Figure indicates the percentage of all avionics failures causing an abort, delay or reduction to a mission.

4. Assessment of supportability to 2010 is taken from the Electronic Warfare Associates - Canada Standard Avionics Specification, July 1990.

FIGURE 4

CC130 Avionics Update - Life Extension

Enhancing Tactical Transport Capabilities: Cockpit Evolution from G222 to C-27J

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Summary
The C-27J is the latest derivative of the service-proven G222 tactical transport. With over 20 years of production and more than 100 aircraft delivered, the G222 has served the military transport needs of Air Forces around the world including the Italian Air Force (AMI) and USAF.

In 1996, Alenia Aerospazio and Lockheed Martin Aeronautical Systems (LMAS) decided to jointly develop the C-27J Spartan tactical transport aircraft. Based on the rugged G222 / C-27A design, the C-27J maintains the existing well-proven military airframe while updating those systems that could best take advantage of state-of-the-art technologies.

The avionics, propulsion, and general aircraft systems were selected for upgrades, including the incorporation of avionics and cockpit upgrades developed for and certified on the LMAS C-130J aircraft.

After a brief historic overview of the G222 family, from its early VTOL roots through intermediate experiences such as the USAF C-27A and Italian Air Force G222 3A avionics modernization program, this paper illustrates the process followed for the development of the C-27J cockpit.

The process used to select a cockpit configuration that allows optimized operational capabilities while reducing overall development costs is presented, together with a description of main cockpit features.

Introduction
The Lockheed Martin Alenia Tactical Transport Systems (LMATTS) C-27J Spartan (see Figure 1) is designed to meet military tactical airlift requirements for a military transport aircraft with high performance, Short Takeoff and Landing (STOL) capability, and low life cycle costs. LMATTS, headquartered in Marietta, Georgia, U.S.A., is equally owned by Lockheed Martin Corporation of U.S.A. and Alenia Inc., a subsidiary of Finmeccanica S.p.A. of Italy. LMATTS manages the design, production, support, and marketing of the C-27J.

Figure 1 – The LMATTS C-27J Spartan

Based on the twin-engine Alenia G222 / C-27A STOL transport aircraft, the C-27J incorporates the same propulsion system and advanced military avionics developed for the LMAS C-130J Hercules, including Allison AE2100 engines with six bladed Dowty R391 composite propellers and an integrated glass cockpit. See Figure 2 for the overall arrangement and features of the C-27J.

The new propulsion system on the C-27J produces up to 36 percent more takeoff thrust than the G222, allowing the C-27J to operate from shorter airfields with greater payload.

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

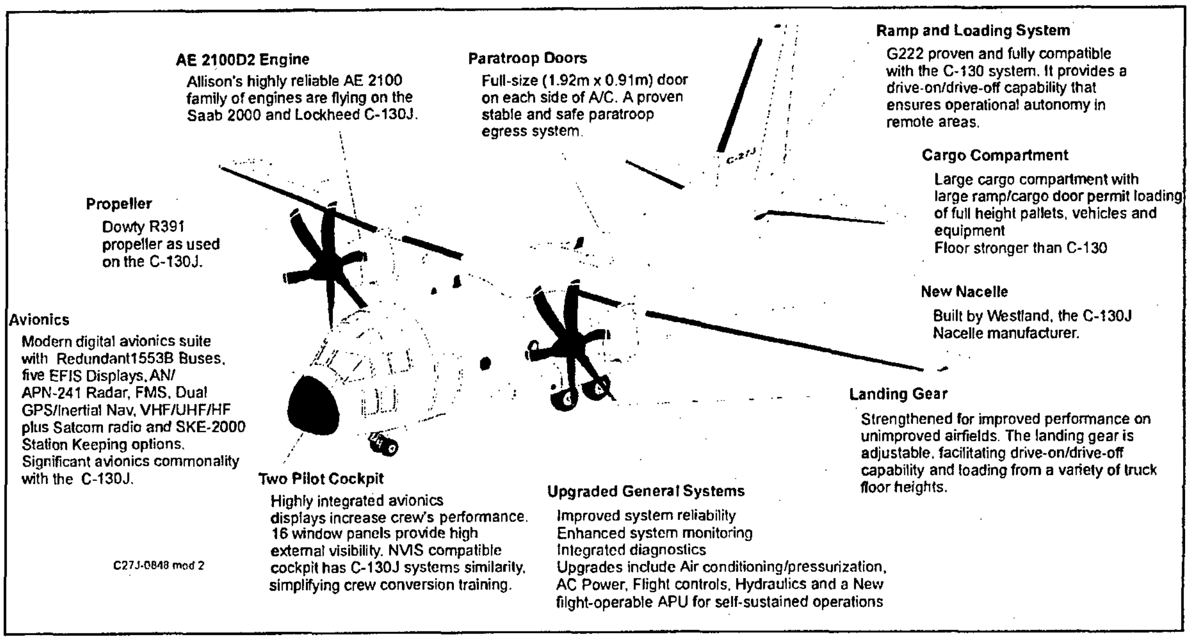

Figure 2 - C-27J Arrangement and Features

Coupled with the C-27J's robust, 3-g capable airframe and maneuverability, the new propulsion system improves the already significant tactical and strategic capabilities of the G222

The C-27J is fully inter-operable with the C-130 family. It carries the same fully loaded pallets using the same loading system. Unlike other light tactical aircraft, it is capable of easily transporting a variety of military equipment (including the HMMWV and Perentie) without disassembly due to its high floor strength and large cargo compartment dimensions. The aircraft can be easily and rapidly reconfigured to perform aerial delivery, CDS drop, LAPES, paratroop drop, troop transport, and Medevac missions. It has a range of 970 nm at a maximum payload of 9,000 Kg (19,871 Lbs).

The C-27J progenitor: the G222

The C-27J is the latest version of a family of tactical transport aircraft that originated at the beginning of the 1960s when FIAT Aviazione conceived the G222 "Cervino" as the Italian answer to the NATO Basic Military Requirement (NBMR) 3 for a vertical takeoff transport aircraft able to be operated at disperse sites without ground infrastructures.

Initially the Cervino had the same twin beam / tails architecture of the Fairchild C-119. The two Rolls Royce Dart RDa turboprops of 3025 SHP each were supplemented by 6 RB 162-2 turbojets to be used for the vertical takeoff and landing. The maximum take-off weight was expected to be in the range of 15,875 Kg (35,000 Lbs).

However this futuristic NATO requirement was never formally launched, so the basic G222 design was modified to a more conventional short take-off and landing configuration, resembling a scaled-down Lockheed C-130, with two General Electric T64-14 turboprops engines with a maximum takeoff power of 3060 SHP each.

Two prototypes were ordered by the Italian Air Force (Aeronautica Militare Italiana - AMI) in 1966, to replace the Fairchild C-119s in their inventory and to fulfil medium transport needs as jointly specified by the Italian military forces.

The No.1 prototype flew for the first time at the Aeritalia[1] test airfield at Torino, Italy in 1970. The two prototype aircraft subsequently entered an extensive evaluation cycle at the Italian Air Force Experimental Squadron (RSV) in Pratica di Mare, near Rome, at the end of which the AMI ordered 44 G222s.

The AMI production aircraft, powered by two GE T64P-4D engines rated at 3400 SHP driving Hamilton Standard 65E60-27 three bladed propellers, are able to carry a maximum load of 9,000 Kg (19,871 Lbs.). The

[1] FIAT Aviazione, Aerfer and Salmoiraghi combined to form Aeritalia in 1969. In December 1990, Aeritalia joined with Selenia to form Alenia.

maximum speed is 285 Knots. The cockpit of the G222 is shown in Figure 3.

Following the AMI, various Air Forces ordered the G222, including the Argentina Army Aviation Command, the Nigerian Air Force, the Somalian Aeronautical Corps, the United Arab Emirates Air Force, the Venezuelan Air Force and the Royal Thai Air Force. In the early 1980s, the G222T with Rolls Royce 20 Mk.801 Tyne engines rated at 5440 SHP and four bladed BAe 4/7000/6 propellers was developed to fulfil a Libyan Arab Republic Air Force requirement for 20 aircraft.

During their operational life, the G222 has been operated in many different operational scenarios, in both peace and war time. Its intrinsic capability to be operated at remote sites with little or no ground support has been demonstrated in humanitarian missions in Europe, Africa and Central and South America as well as in combat operations during the Gulf War and Bosnian crises.

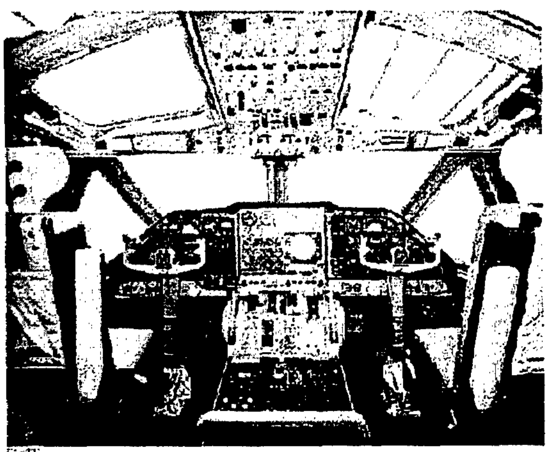

Figure 3 – The G222 cockpit

In their service with the Italian Air Force, a number of G222 variants have been developed to cover specific roles. Among the most noteworthy is the VS (Versione Speciale – Special Version) that uses the basic G222 airframe and accommodates a set of intelligence sensors, managed by eight workstations in the cargo bay.

Another frequently used version is the PROCIV Anti-Incendio (Fire Fighting). In this case, the cargo bay accommodates a special tank with 6000 liters (1560 US gallons) of fire retardant. The liquid retardant is sprayed through nozzles that extend through the cargo ramp.

While the G222 began as a military transport, the Fire Fighting version of G222 has been certified (as the G222R) by the Italian civil certification authority Registro Aeronautico Italiano (RAI) in the "Categoria Limitata" of RAI-RT Parte 225 (the RAI equivalent of FAA Limited Category per FAR 21.25).

The C-27A Spartan

In the late 1980s, the United States Air Force issued a specification for a tactical transport aircraft that could operate in rough fields of approximately 500 meters in Central and South America.

The aircraft selected to fill this role was a variant of the G222 known as the C-27A. The Alenia G222 were modified by Chrysler Corporation to incorporate a new radio communication set. The C-27As were powered by two Fiat built GE T64-P4D turboprops rated at 3,400 SHP each.

Ten C-27A Spartans were delivered to USAF starting in 1991. These aircraft have been operated by the 310th Airlift Squadron at Howard Air Force Base, Panama, flying a variety of missions in the region, including humanitarian assistance, peacekeeping and counter drug missions, and accumulated over 36,000 flight hours.

The G222 3A

In 1996 AMI began an update program on their G222 tactical transport. Actual operational use, particularly during the humanitarian operations in Bosnia and Somalia, had demonstrated to the AMI the advantages of updating certain aircraft systems.

These updates include an enhanced self-defense capability, the capability of night operations using Night Vision Goggles (NVGs), bubble windows for observers, removable cockpit armor, an OBIGGS and updates to the communications and navigation systems to replace obsolete equipment.

To respond to these requirements the G222-3A version has been developed by Alenia. The first aircraft modified to the 3A standard is planned to fly before the summer of 1999.

From the C-27A to the C-27J Cockpit

At the beginning of the C-27J program, it was clear that, more than 30 years from its conception, the basic G222 aircraft was still uniquely qualified to satisfy world-wide operational needs for medium size tactical transport. One of the big advantages of the G222 / C-27A configuration against its competitors is the outstanding outside visibility afforded by 16 cockpit windows, including 4 roof (overhead) and 4 chin (drop zone) windows. This configuration offers a vital advantage in tactical operations such as low level flight in mountainous terrain and low altitude aerial delivery.

However, it was apparent that a modernization of the G222/C-27A configuration was needed, following a path similar to that recently used on the LMAS C-130J program. In articular, it became evident that major operational advantages could be gained by updating the powerplant and avionics systems.

In addition, the commonality and interoperability with the C-130 Hercules would offer Customers a "family" of transport aircraft to satisfy their operational needs.

An important decision taken at the beginning of the C-27J program was to apply for both military and civil type certifications, in order to satisfy the most stringent requirements of potential customers. This decision was also influenced by the positive results of the civil certification process leading to the G222R Fire Fighting version. The most practical result of this decision has been its influence on the aircraft design, including the cockpit, in order to meet both the most recent JAR 25 requirements (the selected civil regulation for the C-27J) and applicable military standards.

The parallel civil and military certification programs involve the RAI and the Italian MoD. Three prototype aircraft will be involved with flight test beginning in the summer of 1999.

One of the most challenging parts of the C-27J program has been to propose to potential Customers a tactical transport aircraft with outstanding capabilities while maintaining low acquisition and operational costs. The C-27J is unique among competitors in offering a configuration optimized for actual military requirements; acquisition budget limitations are now commonplace, so the real challenge is to meet stringent requirements at a reasonable cost.

These considerations led LMATTS to adopt a "commercially oriented" design and procurement approach as well as adopting a program-wide system engineering methodology. Also, the use of off-the-shelf equipment has had the effect of reducing non-recurring costs. In striving toward the stated program goals, commonality with C-130J often proved to be the most cost-effective option.

This has been particularly true for the cockpit design. The 1970s vintage control suite and electro-mechanical instruments of the G222 appeared to be a prime candidate for updating. In the feasibility study that led to the C-27J, a number of different upgrade options were considered. A trade study among these different options was accomplished with the involvement of the most innovative avionics suppliers.

The options explored included off-the-shelf equipment such as those used on commercial airliners. In trade study evaluations, these options resulted in low performance scores that indicated a fundamental incompatibility with military requirements and tactical operations, and were therefore eliminated. At the end of this competition, taking into consideration marketing surveys as well as experience gained by LMAS in developing and marketing the C-130J to the USAF, UK Royal Air Force, Royal Australian Air Force and Italian Air Force, a decision was made to adopt an avionics system and displays and controls configuration based on the C-130J hardware and software.

The major advantage of the selected solution is the lower development, integration and certification / qualification risk made possible by a reuse policy from C-130J. In addition the intrinsic flexibility of the MIL-STD-1553B bus architecture provides for the addition of equipment such as defensive and other mission systems to meet peculiar Customer requirements.

As far as the cockpit is concerned, the major differences from the C-130J are 1) Head Up Displays (HUDs) are an option rather than baseline equipment and 2) re-packaging of some multi-function control panels to suite the smaller C-27J glareshield panel and central console.

To develop the C-27J cockpit, an integrated Alenia and LMAS team was established, formed by aircraft systems and installation design specialists, human factors engineers and pilots. Different tools have been used in the development of the cockpit configuration, including a digital mock-up on CATIA workstations and an ergonomic physical mock-up of the complete flight station. The mock-up has since been modified to serve as a C-27J flight simulator.

The C-27J Cockpit and Avionics

The C-27J cockpit (see Figure 4) allows for a crew of two pilots to perform logistical and tactical airlift mission operations in day, night, visual and instrument meteorological conditions using standard operational procedures.

The cockpit is arranged in a standard side-by-side configuration. The dual control yokes and rudder pedals retain the G222 / C-27A arrangement. Other controls required for operating the aircraft, such as flaps and trim controls are located on the central console within easy reach of both pilots, enabling either pilot to control the aircraft.

A handle located in front of the left side console, operated by the pilot provides nose-wheel steering control.

A single throttle quadrant assembly with a single lever for each engine is located in the center console, easily accessible to either pilot. Angular position of the two levers is transmitted to the proper Full Authority Digital Engine Control (FADEC) via electrical signals.

An additional member (i.e. a loadmaster, tactical support personnel or observer) can be seated in a third foldable seat behind the central console to support high workload missions.

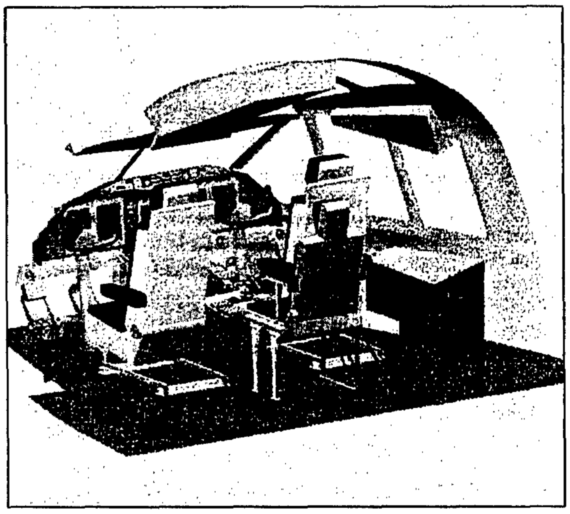

Figure 4 – The C-27J Cockpit Layout

A major design goal in the development of the C-27J cockpit was to produce a dark cockpit, i.e. using a minimum number of mode lights. In fact, if a system is in its normal operation mode, no annunciator lights are illuminated: only when a system leaves (or is commanded to leave) its normal operating mode are control panel annunciator lights illuminated. By minimizing normal mode lights and annunciating only abnormal conditions, the time and effort required for the pilots to scan control panels for abnormal conditions is reduced.

Main Instrument Panel

The Main Instrument Panel contains five Active Matrix LCD Color Multipurpose Displays Units (CMDUs), the Integrated Standby Instrument and other general systems displays and controls (see Figure 5).

The overall layout of the Main Instrument Panel has been designed to maintain clear out-of-the-window visibility while allowing an uncluttered configuration of displays and controls.

The glareshield (see top of Figure 5) contains the Digital Autopilot / Flight Director controls and displays. Located within easy reach of either pilot, this arrangement of autopilot controls provides clear mode awareness while maintaining out-the-window visibility

The Reference Set control panels are also located on the glareshield, providing a means for the pilot and copilot to set the reference barometric setting, airspeed and altitude. Master Caution and Master Warning indication and cancel functions are also provided.

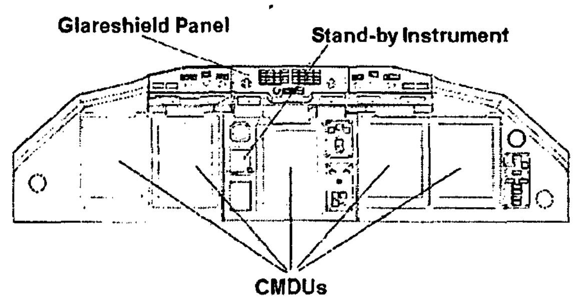

Figure 5 - Main Instrument Panel

The Center Console (see Figure 6) accommodates three rows of ARINC standard control panels. This configuration allows flexibility in the installation of panels and makes it possible to cater for Customer-unique requirements or growth.

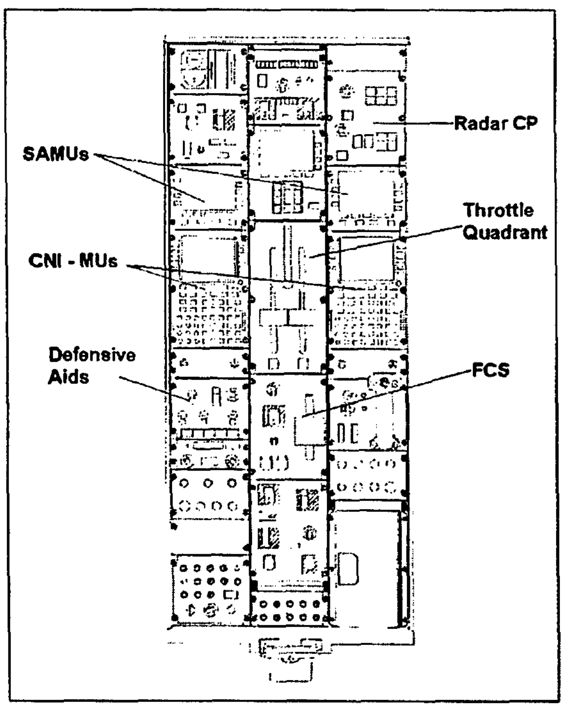

Figure 6 - Center Console

The design of the console allows easy access to control panels by both pilots while the rear part of the console accommodates equipment for the additional crew member.

The Overhead Panel (see Figure 7) integrates general aircraft systems displays and controls, allowing accessibility by both pilots. It also contains flight essential circuit breakers to satisfy JAR 25 requirements for a two-pilot cockpit.

Like the center console, the overhead console uses a three-row configuration with quick-disconnect rails to improve maintainability, thus allowing easy access to the panels and providing flexibility and growth capacity.

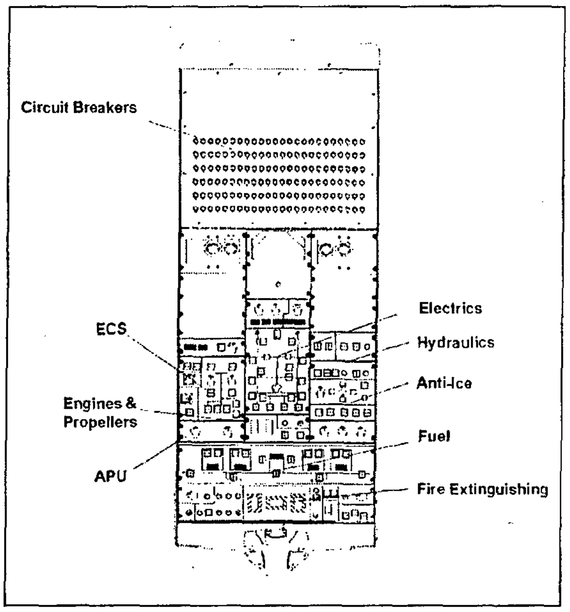

Figure 7 - Overhead Console

The lower side consoles are reserved for control functions that can be dedicated to a single pilot. Stowage for charts, handbooks and other small loose equipment is provided.

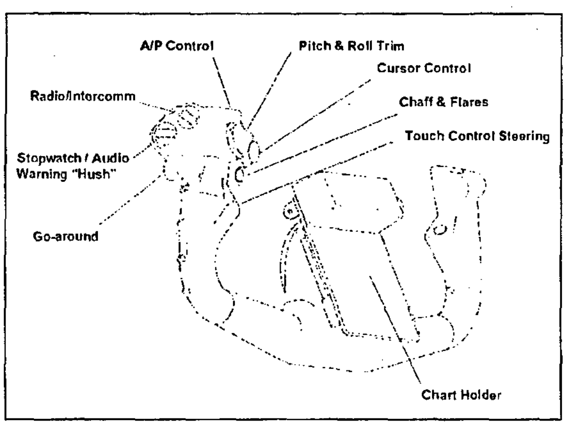

Figure 8 – Pilot's Control Yoke

The Control Yokes (see Figure 8), while maintaining the basic configuration of G222/C-27A, have been modified with ergonomically designed grip controls that provide quick access to certain functions while keeping the pilot's hands on the control wheel during workload intensive missions

Displays

The C-27J has an integrated head down display system that is optimized to provide the pilots with the type and amount of information they need at the time they need it.

Primary flight information and guidance as well as navigation, power plant and fuel system information is available on the five head down CMDUs mounted in the main instrument panel. These displays have a viewing area of 6 inches horizontally by 8 inches vertically.

CMDUs present information in a number of formats that have been derived from those available on C-130J and adapted for the C-27J configuration.

These displays formats have been carefully designed using established human engineering guidelines and operational standards. They have been validated in engineering flight simulations as well as during flight tests with the participation of company, military and Certification Authority pilots. In fact, the basic C-130J display formats (PFD, NAV, Engine, etc.) have been certified under FAR Part 25 by the US FAA.

The available formats include:

- Primary Flight Display (PFD)
- Navigation and Radar Display (NAV)
- Digital Map Display
- Engine, Fuel and Advisory, Caution and Warning System (ACAWS) Display
- ACAWS Overflow Display
- Fault Log

Each of the CMDUs is capable of displaying any of the available formats: however, the two outboard CMDUs are normally dedicated to Primary Flight Display formats while the center CMDU presents the Engine, Fuel and ACAWS format.

Selection of the formats to be presented as well as of the presented display parameters is commanded by the pilots through two (pilot and copilot) Single Avionics Management Units (SAMU) located on the Center Console (see Figure 6).

The incorporation of multi-function displays in the C-27J cockpit eliminates the need for more than 50 electro-mechanical displays previously used in the G222 / C-27A cockpit.

CMDU Formats

The C-27J PFD format presents vital flight information (i.e. airspeed, attitude/flight path, altitude and horizontal situation) in a standard "T" arrangement. Additional data available on the PFD includes autopilot mode annunciators, radar altitude, flight director, clock, and stopwatch indications as well as data from the Traffic Alerting and Collision Avoidance System (TCAS).

The C-27J NAV format provides an expanded view of the aircraft horizontal situation. On this format it is possible to overlay flight plan information, waypoints, airport locations, and threats.

This integrated display includes data such as time on target, bearing and distance to waypoints, estimated time of arrival, clock and stopwatch readouts. The capability to overlay high resolution color weather radar, ground mapping radar and TCAS greatly enhances the pilots' situational awareness and simplifies the task of aircraft navigation.

The Digital Map Display Format presents current aircraft position superimposed on digitized maps from a Digital Map Unit. Overlays on this display such as flight plans are also available to reduce the need for pilots to consult paper maps and manually track aircraft position relative to terrain features on low level routes. This has the overall effect of increasing pilot's situational awareness while significantly reducing workload associated with aircraft navigation.

The ability to pan to different areas of the digitized map and zoom in for details further enhances the utility of this display.

The Engine, Fuel and ACAWS Display format provides the pilots with vital engine operating parameters, fuel content indications and plain text advisories, cautions and warnings related to the aircraft systems and operational conditions.

Color coding of engine indications and automatic color changes during exceedences simplify the task of engine performance monitoring.

The ACAWS greatly reduces the need for the pilots to constantly monitor aircraft systems, thus enabling them to concentrate on performing their mission. See below for additional information on ACAWS.

In the unlikely event that there are more cautions and warnings present that can be shown on the main Engine, Fuel and ACAWS format, additional messages are automatically displayed on the ACAWS overflow format, presented on another CMDU according to well defined algorithms.

The Fault Log Format presents detailed information on certain ACAWS messages and certain non-flight related faults. Cautions and advisories that the pilots have stored from view on the main Engine, Fuel and ACAWS page also appear on this format.

Standby Instruments

The Integrated Standby Instrument, located in the main instrument panel, provides independent sources of airspeed, altitude, attitude, and magnetic heading on an NVIS compatible color LCD display.

The Standby Instrument is powered by the Emergency DC electrical bus and remains powered if all electrical generating capability is lost. Remote sensors for pitot/static data and heading, along with internal sensors for attitude, are integrated in the standby instrument to provide for continued safe flight in the unlikely event that all CMDUs are lost.

In addition, an electromechanical Clock / Stopwatch is available to display time of the day and to provide a back-up stopwatch.

Advisory, Caution And Warning System (ACAWS)

Monitoring of critical operational and systems conditions and annunciation of failures associated with those systems are performed by the ACAWS. This reduces the monitoring load on pilots and allows them to concentrate on mission oriented duties.

ACAWS takes advantage of the availability of data on the digital avionics architecture to collect aircraft systems faults, out-of-tolerance values and to display appropriate annunciations to the pilots in a centralized location.

Presented by default on the center CMDU in the main instrument panel, ACAWS messages take the form of plain text advisories, cautions and warnings that are accompanied by aural alerts.

Pilot attention is also captured by means of two master caution / master warning lights (one for each pilot) located on a primary area of vision on the glareshield panel.

Dedicated text and voice messages are also available for special alerts related to flight critical conditions. For example, a stall warning system provides the pilots with an indication of dynamic stall speed and alerts the crew when the aircraft is approaching a stall condition by triggering "STALL, STALL" aural and visual messages and by shaking the control column.

Flight Management System (FMS)
The C-27J Communication, Navigation and Identification Management System (CNI-MS) performs the functions of an FMS. The CNI-MS provides a high level of automation and designed-in flexibility.

The flight crew interface with the CNI comprises two CNI Management Units (CNI-MU) located in the cockpit center console (see Figure 6). All mission planning and control tasks are performed through the CNI-MU. They are positioned to allow optimum head down access by each pilot.

The CNI-MS controls all communication and navigation functions as well as performing the primary flight management processing, including flight planning and calculation of guidance commands. Identification system (IFF) management is also performed through the CNI-MS.

Radio tuning can also be performed through the Communication Navigation Radio Panel located in the forward part of the center console, in a central position that allows comfortable use by both pilots.

Digital Autopilot / Flight Director System
Dual Digital Autopilot / Flight Director (DA/FD) systems provide several functions including basic aircraft stabilization and attitude control, flight director commands for controlling altitude, speed and heading, and specific guidance for take-off, flight plan following, approach and go-around phases of flight.

In addition a Touch Control Steering (TCS) function is available through a pushbutton switch on the control yokes that allows the pilots to manually adjust the aircraft pitch and roll attitude with column and yoke movements when an autopilot mode is active. When the TCS control is released, the autopilot recouples the selected lateral mode and maintains the pitch attitude existing at switch release.

The DA/FD interface in the cockpit is provided by the glareshield mounted control panels as well as appropriate symbology presented on the PFD format of the CMDUs. Heading and course reference selection is provided by the pilot's and copilot's Heading/Course Set Panel on the center console.

Cockpit Lighting System
The Cockpit Lighting System includes primary lights (i.e. all integrally illuminated components such as instruments, control panels, numeric displays, etc.) and secondary lights (i.e. dome, flood, wander lamps, and chart holder lights).

All internal lights incorporate NVIS compatible modes per MIL-L-85762A. In addition, the dome lights can be operated in dual NVIS compatible and normal mode. A thunderstorm mode is also available.

A dimming function is provided for all primary lights and for dome, flood, wander and chart holder lights. Lighting control is designed to provide control across all ambient conditions. Cockpit lighting control is divided by zones and allocated to pilots according to a specific control philosophy to ease workload.

The C-27J Flight Simulator
As previously discussed, the C-27J has been developed with the use of a Flight Simulation facility located in the Alenia Aeronautica plant in Torino, Italy.

This facility has been used in the development of the cockpit ergonomic design as well as development of the flight controls system and integration of the new powerplant. It will also be used to prepare for and support flight test activities.

The Flight Simulator, developed as an ergonomic mock-up used in the initial phases of the program, comprises a complete fixed-base flight station equipped with a Computer Generated Imagery (CGI) system. The CGI system projects the external world onto screens located in front of the cockpit windows.

The flight simulator cockpit is equipped with a mix of commercial off-the-shelf displays and controls, G222-standard equipment such as seats, control columns and rudder pedals (that are unchanged on C-27J) and some custom built equipment such as the new throttle quadrant and flap control assembly.

All simulation software has been developed internally by Alenia, based on experience gained in the AM-X and Eurofighter 2000 programs. A complete aeromechanical simulation model is available, together with models of the engines, flight controls and main general aircraft systems. Avionics simulation currently allows performance of basic navigation tasks.

This initial configuration is being updated to become a full mission simulator. Real C-27J cockpit hardware is being installed together with a Control Loading System developed by Fokker Control Systems to simulate control loads in the complete flight envelope. A new visual system with collimated optics will be installed to enhance visual realism.

This updated Flight Simulator configuration will enable Customers to perform initial aircrew familiarization training.

Conclusions

The LMATTS C-27J is the only medium size transport aircraft on the market designed for military operations that provides a state-of-the-art glass-cockpit expressly conceived for tactical operations.

Backed by an avionics system based on a flexible and expandable MIL-STD-1553B bus architecture, the C-27J cockpit has retained the overall, mission-proven geometric configuration of the G222 / C-27A enabling the two-pilot flight deck crew to perform foreseen missions more accurately with reasonable workload levels.

Development of the C-27J cockpit demonstrates that introducing state-of-the-art technology in a sound aircraft design is a viable means of satisfying the current and future needs of worldwide operators.

List of Abbreviations

AC	Alternating Current
ACAWS	Advisory, Caution And Warning System
AMI	Aeronautica Militare Italiana
ARINC	Aerospace Radio INCorporated
A/C	Aircraft
A/P	Autopilot
CDS	Container Delivery System
CGI	Computer Generated Imagery
CMDU	Color Multipurpose Display Unit
CNI	Communications, Navigation, Identification
CP	Control Panel
DA/FD	Digital Autopilot / Flight Director
DC	Direct Current
ECS	Environmental Control System
EFIS	Electronic Flight Instruments System
FAA	Federal Aviation Administration
FADEC	Full Authority Digital Electronic Control
FAR	Federal Aviation Regulations
FCS	Flight Control System
FMS	Flight Management System
GPS	Global Positioning System
HF	High Frequency
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HUD	Head Up Display
INS	Inertial Navigation System
IFF	Identification Friend or Foe
JAR	Joint Aviation Requirements
LAPES	Low Altitude Parachute Extraction System
LCD	Liquid Crystal Display
LMAS	Lockheed Martin Aeronautical Systems
LMATTS	Lockheed Martin Alenia Tactical Transport Systems
MoD	Ministry of Defense
MS	Management System
MU	Management Unit
NATO	North Atlantic Treaty Organization
NAV	Navigation
NVG	Night Vision Goggles
NVIS	Night Vision Imaging System
OBIGGS	On Board Inerting Gas Generation System
PFD	Primary Flight Display
RAI	Registro Aeronautico Italiano
RSV	Reparto Sperimentale Volo
SAMU	Single Avionics Management Unit
SHP	Shaft Horsepower
STOL	Short Take-Off and Landing
TCAS	Traffic Collision Avoidance System
TCS	Touch Control Steering
UHF	Ultra High Frequency
UK	United Kingdom
US	United States
USAF	United States Air Force
VHF	Very High Frequency
VS	Versione Speciale
VTOL	Vertical Take-Off and Landing

Acknowledgements

The Authors wish to thank all the members of the Alenia / LMAS Cockpit Design Built Team in Torino, Pomigliano and Marietta whose work has been an essential background for the preparation of this paper.

Additional information on the C-27J Spartan is available from:

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Or visit the C-27J website at:
http://www.lmasc.com/c-27j/index.htm

A MODERN INTEGRATED AVIONICS SYSTEM FOR THE NEXT GENERATION U.S.M.C. ATTACK AND UTILITY HELICOPTERS

SUMMARY

The United States Marine Corps awarded the first phase of the H-1 platform upgrade program to Bell Helicopter in late 1996. This effort resulted in substantial improvements to both the AH-1 Gunship and UH-1 Utility aircraft. Upgrades included a new transmission and a 4-bladed rotor with resulting improvements in mission effectiveness and cost of ownership. In 1997, the program was expanded to provide a modern suite of avionics incorporating improved sensors, cockpits, weapons processing, helmet-mounted displays and an advanced centralized mission processing subsystem. This technical paper will review the basis for architectural decisions of the avionics and the criteria for selection of key sensors and displays. Major attributes of redundancy and commonality are described, together with an overview of an advanced open architecture mission computer.

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INTRODUCTION

The H-1 Integrated Avionics System (IAS) responsibility was given to Litton Guidance & Control Systems in August of 1997 as an extension to major ongoing upgrades to AH-1 and UH-1 airframes. The contract requires delivery of cockpit displays and controls, helmet display subsystem, communications, navigation, wing stores weapons management system, turreted 20 mm gun control, and a central mission computing subsystem. Since then, Lockheed Martin Corporation has been selected to provide a long-range Target Sighting System consisting of a third generation FLIR, color TV, and laser subsystem, complementing the Hellfire missile used in the AH-1.

Airframe improvements include a new 4-bladed composite rigid rotor and drive system, new tail rotor, increased horsepower, accommodation of increased crash loads, improved payload accommodations within the UH-1, added weapons stores station on the AH-1, and an increase in fuel capacity. These improvements, together with the new avionics, will deliver the most affordable and technically advanced helicopters geared for the new mission roles anticipated over the next 25 years. Figure 1 illustrates the scope of these upgrades as they apply to the AH-1, now called the AH-1Z, with similar scope of improvements to the UH-1Y. In total, these new configurations benefit from 55 percent commonality by weight, 60 percent by costs, and 85 percent for significant maintenance items, and result in substantial increases to payload, range, and affordability.

This upgrade was preceded by a series of studies to determine the most cost-effective way of optimizing helicopter warfighting capability for the diverse mission roles of the U.S. Marine Corps. Enhancements to both platforms resulted in:

- Improved mission capability
- Increased performance and maneuverability
- Additional features for survivability
- Reduced pilot workload
- Increased growth potential

Recognition that these platform types will be accepted into service in a new generation of threat has shaped the decisions both for the basic platforms and avionics.

Warfighting requirements and the identification of those technologies needed to support them are derived from the U.S. DoD analysis and directives contained within Joint Vision 2010. In some regards, this listing of about one dozen supporting objectives have all influenced the AH-1Z and UH-1Y products, but primarily the avionics upgrade is linked to:

- Information superiority
- Application of precision force
- Improved combat identification
- Military operations in urban terrain
- Improved capability for Electronic Warfare (EW)

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

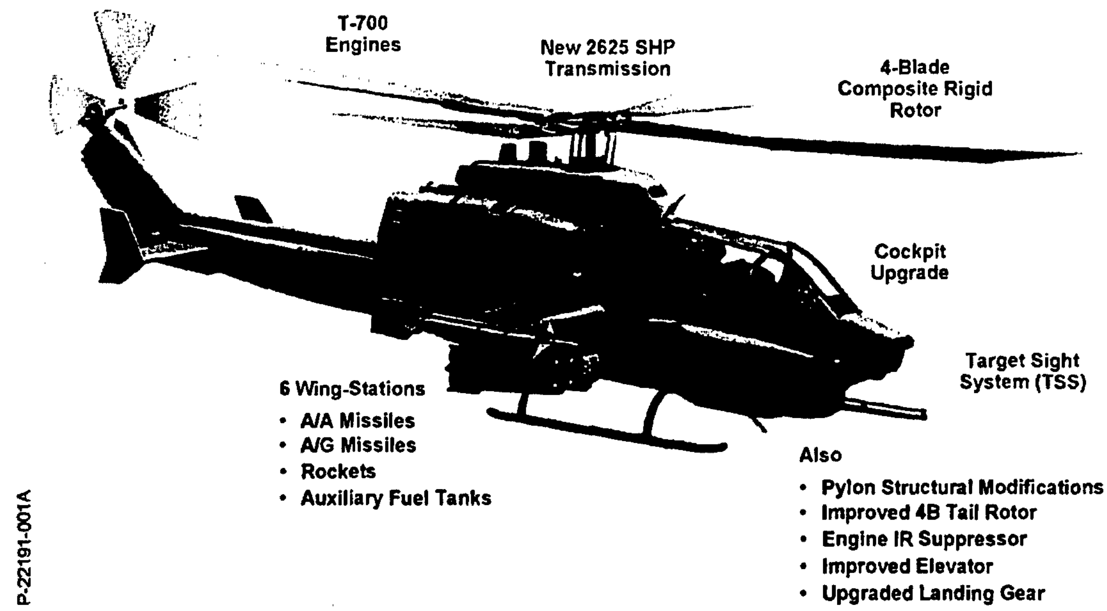


Figure 1. Scope of Upgrades

Diversity of the U.S. Marine Corps charter demands more mission versatility than the specialized helicopter gunship solutions of the past decade, and illustrates a profound shift from the linear battlefield expectation considered in the older culture of designs, to a theatre of operations addressing deployment in a Network Centric setting; autonomous or detached authority; and low intensity conflicts seeking targets of opportunity.

It is appropriate to consider further, the demands of Joint Vision 2010 and recognize that attainment of information superiority is achieved with excesses of "bandwidth, storage, and processing." This is the means to achieve capability in the Network Centric Warfare setting: a situation in which diverse resources of land, sea, and air will exchange complex information to execute time critical missions. These data types are expected to include broadcasted maps, video mosaics, retargeting directives, and a variety of large database retrievals. This has been the basis for development of a modern general purpose Mission Computer, delivering enormous built-in growth, with upgrade paths linked to this future technology base. It also has been pivotal in the decision to select a centralized architecture of processing, video/graphics, communications data linking, and opportunities for large database access. Shown in Figure 2 is this approach concept which links complex onboard information with realtime data updates into aviator useable format.

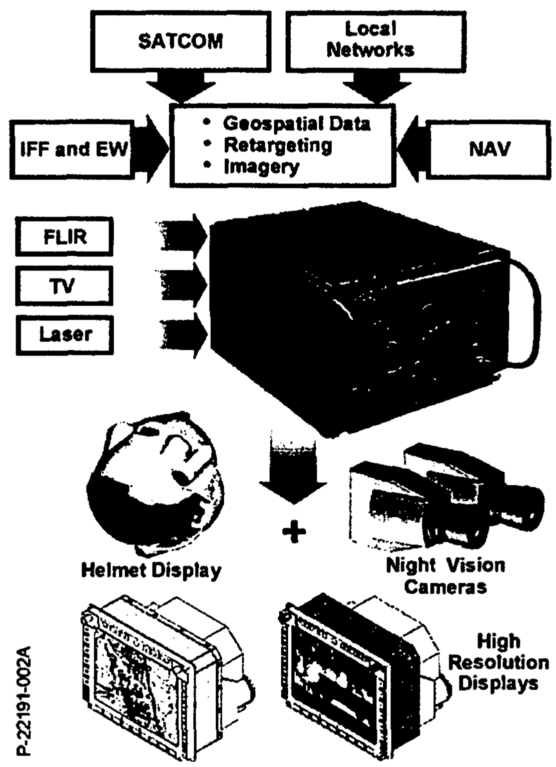


Figure 2. Centralized Processing of Data, Graphics, and Video to Support Information Fusion

COMBAT VISION – "THE GUNSHIP NEED FOR SITUATIONAL AWARENESS"

The supporting objectives identified in Joint Vision 2010 and the added needs in a U.S. Marine Corps mission are best realized by improvements to situational awareness. It is here that the technologies and mission execution effectiveness optimally merge. Specifically, it is necessary to give the aviator capabilities for:

- Execution of time critical missions
- A consistent understanding of the battlespace
- Accommodation within a communication grid of assured services
- Assured combat identification

This avionics upgrade delivers the most modern combination of sensors, displays, and information gathered to meet these needs, as depicted in Figure 3. This is a solution satisfying demands for advanced tactical communications, improved electro-optical/ infrared imaging, inherent bandwidth and throughput, and of course, crew interfaces including high resolution color MFDs, and a full-function helmet-mounted display.

Helmet-Mounted Display

The advantages of a helmet-mounted display in a helicopter gunship are well recognized. However, a full functional capability which provides total symbology needs in an unambiguous see-through visor has heretofore not been achieved. The challenges are substantial, but the value to the aviator and the mission are profound. Developed as part of the Integrated Avionics System (IAS), this subsystem satisfies all the needs for basic aviator safety, optical performance in full daylight mode,and most impressively, has exceeded the night pilotage specifications using clip-on image intensified cameras.

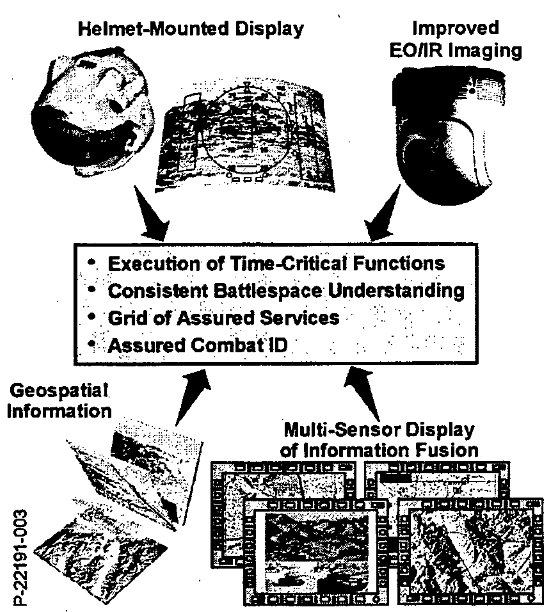


Figure 3. Situational Awareness and the Gunship Mission

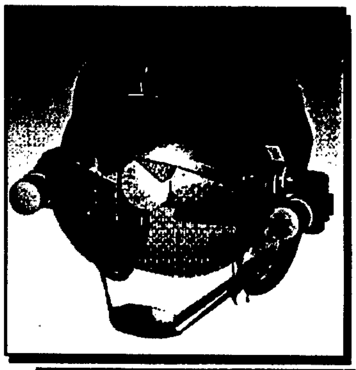
In keeping with the system architecture for central mission processing, these functions are integrated within the Mission Computer, allowing video access paths to exist for future accommodation of FLIR imagery projection on the visor and capture of helmet camera video for storage and display. It is also in this setting that camera sensor processing, symbol creation, and tracker to weapons control is achieved. The basic helmet-mounted display is a binocular projected system, in which the projected CRT sources are delivered to a see-through visor without the hindrance of in-line optical combiners. This design approach allows for excellent exit pupil and eye relief, and from this is realized the ability to accommodate nuclear/ biological/chemical protection equipment. Figure 4 shows the physical configuration of the helmet with two cameras attached, with summaries of performance.

Military Operations in Urban Terrain and Enhanced Night Pilotage

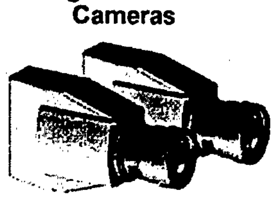
Requirements for total situational awareness reach their peak when responding to the needs of military operations in urban terrain (MOUT). It is here that maneuverability, survivability, engagement, and the support of C^4I (command, control, communication, computers, and Intelligence) interact at the highest level of conflict intensity. This demands the best human interface features, and the unequalled advantage of both crewmen looking up and out. This need emphasizes the value of a see-through helmet-mounted display with its ability to cue or steer weapons and sighting systems rapidly to targets. This demand is raised to a higher level of criticality when executed at night; yet, this is the anticipated mission role for this next generation gunship.

Until now, night pilotage has been made possible through the use of either head down thermal imaging sensors or the aviator night vision image intensified goggles. The AH-1Z requires that low light intensified imagery from the clip-on cameras be presented within the helmet and correlated with outside (see-through) information, overlayed with cueing and flight symbology. It has been necessary to develop the most advanced high resolution I^2 (image intensified) camera for this application. This design exceeds the minimal-needs with either of the redundant clip-on cameras giving projected night pilotage superior to Generation III OMNI III direct view goggles.

Additional technology has been developed in the form of low halo I^2 tubes, and anti-blooming processing to address the effects of halos from bright objects. This is always a shortcoming with night vision devices, but represents a very serious problem for military operations in urban warfare environments.



Clip-On
Image Intensified
Cameras



Helmet Display Performance to Requirements	Requirement	Provided
Field of View	40° Horiz, 30° vert	40° Horiz, 30° vert
Ambient Light Environ	To 10,000 ft-L	Sun Visor: >10,000 ft-L Clear Visor: 8,750 ft-L
Resolution and MTF	MTF>0.29 at 0.86 cy/mR	MTF=0.47 at 0.86 cy/mR
Display Viewing	Biocular or Binocular	Binocular
Head Supported Weight	4.8 lb, max.	4.74 lb (including cameras)
CG with Headform	Within Limits for Crash Safety	Within Limits for Crash Safety
Exit Pupil	15 mm (min.)	15 mm
Eye Relief	25 mm (min.)	70 mm
Interpupilary Adjustment	5th to 95th Percentile	5th to 95th Percentile
Secondary Reflection	<7% (threshold), <3% (goal)	1%
Display Update Rate	15 Frames/Sec (threshold) 30 Frames/Sec (goal)	30 Frames/Sec

- Fully Redundant Night Vision Capability
- Performance for Resolution Over Luminance Range in Access of Omni III Goggles
- Improved Intrascene and Interscene Dynamic Range
- Low Halo I^2 Tube with Anti-Blooming Technology

P-22191-004

Figure 4. Performance and Mechanization Overview of the Advanced Helmet-Mounted Display System

Target Sight System

The advanced capability of the long-range target sighting system shown in Figure 5 is at the heart of stand-off weapons delivery, and is the essential sensor to complement the laser homing Hellfire Missile. Contained within a large internal volume gimballed turret assembly are three essential sensors:

1. Third generation I_nS_b midwave FLIR, with a large 8.55-inch (22 cm) aperture
2. TV system consisting of a 0.88° to 15.10° F.O.V. zoomable color camera
3. Long-life laser designator/range finder

With the gimbals internally stabilized using a fiber optics inertial sensor unit to within five µradians and with computer-based image capture and stabilization, this system provides acquisition and positive target identification displays through the full range envelope of the missile.

This true third generation FLIR provides unmatched operational performance in its support of precision guided and ballistic weapons.

Full Authority Dual Cockpits

Commonality of avionics components, including high resolution color MFDs; cyclic, collective and mission grips; backup instruments; and keyboards, are provided for both the AH-1Z and UH-1Y. Cockpit layout and human interaction are also made common to the maximum extent possible for like functions. The advantage of this to the U.S. Marine Corps includes reductions in: documentation costs, training costs, logistics costs; and the opportunity for flexible crew assignments.

Within the specific platform type, full flight and mission execution capability and authority is provided to both aircrew positions. In the gunship variant (AH-1Z), both front and rear seat positions have full control for flight, have full weapons authority, have full access to the target sighting system and of course, both front and rear aviators are equipped with helmet display subsystems.

- A true 3rd generation FLIR providing unmatched performance
- Target detection, recognition, and positive ID at and beyond maximum weapons range
- Primary sensor to support accurate delivery of precision guided and ballistic weapons

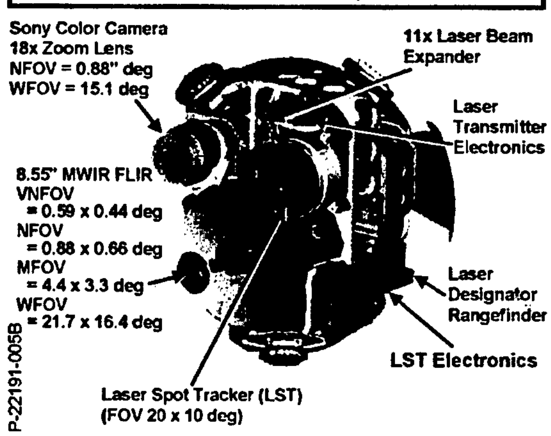


Figure 5. Long-Range Target Sighting System

This cockpit design feature positively impacts all of the overarching upgrade objectives in that it:

- Lowers acquisition cost and life-cycle cost
- Improves survivability and probability of mission success
- Enhances situational awareness
- Reduces pilot workload

This all-glass cockpit for the AH-1Z is shown in Figure 6, and features the most advanced displays adapted from commercial applications. Specifically, the color MFDs are high resolution (1024 x 768 pixels) units in an 8-inch x 6-inch (20.3 cm x 15.2 cm) viewing area, with performance under conditions of full sunlight or at night vision levels. The viewing cone exceeds ±40° vertical and approaches ±60° horizontal with excellent contrast ratios. In addition, these displays are connected to the graphics subsystems of the mission computer through high bandwidth digital interfaces so that perfect registration of pixel to graphics source is maintained in a secure electro-magnetic compatibility (EMC) installation.

Data entry displays are 4 inches x 4 inches (10 cm x 10 cm) units which also serve a dual purpose as the emergency backup instrument readout.

WEAPONS VERSATILITY AND FIRE POWER "APPLICATION OF PRECISION FORCE"

Weapon Versatility

The new AH-1Z weapons and ordnance array is the most diverse of any helicopter in the world today. Furthermore, with the full control authority given to each crewmember, engagement of separate targets can be achieved simultaneously. Figure 7 shows the AH-1Z weapons systems diversity and capacity based on the upgrade to four universal weapons stations and two wing-tip stations.

The primary antitank weapon is the AGM-114 Hellfire, which can deliver high explosive, shaped charge warhead over ranges in excess of 10 km. With target acquisition, detection and laser designation using the target sighting system, this missile uses its semi-active homing seeker either in a Lock-on Before Launch (LOBL) or Lock-on After Launch (LOAL) mode. The AGM-122 Sidearm is the second type of air-to-ground missile equipped with wideband radiation head seeker. Air-to-air engagements use the AIM-9 Sidewinder with supersonic heat seeking target closure over ranges up to 16 km.

The 20-mm turreted gun is the quick reaction weapon of choice, particularly for area suppression or close range air-to-air gunnery. This weapon can be deployed in a helmet or target-sighting system steered mode or can be set to a fixed forward firing position. Delivering 20-mm high explosive shells at approximately 630 rounds per minute, this 3-barrel Gattling gun is a formidable weapon.

Either 7 or 19 round rocket pods are available in the weapons complement. These are standard 2.75-inch (7 cm) rockets for air-to-ground use with a variety of warheads including flechettes, smoke, illumination, and high explosion antitank (HEAT).

It is the avionics system that combines these missiles, rockets, and guns into a powerful integrated suite of weapons. This is achieved by coupling the acquisition and control of the weapons to the sighting and helmet systems, and through the accuracy enhancements of computer-based fire control processing. The improvements to guns and rockets, as a result of the integrated avionics system fire control processing, are shown in Figure 8.

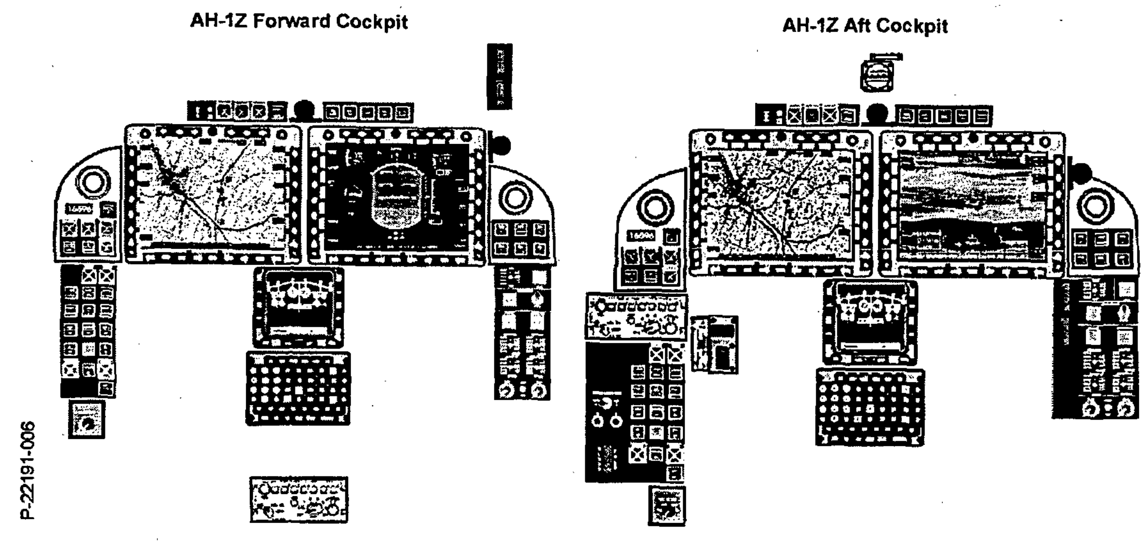


Figure 6. Fight or Flight Authority from Both Aircrew Location

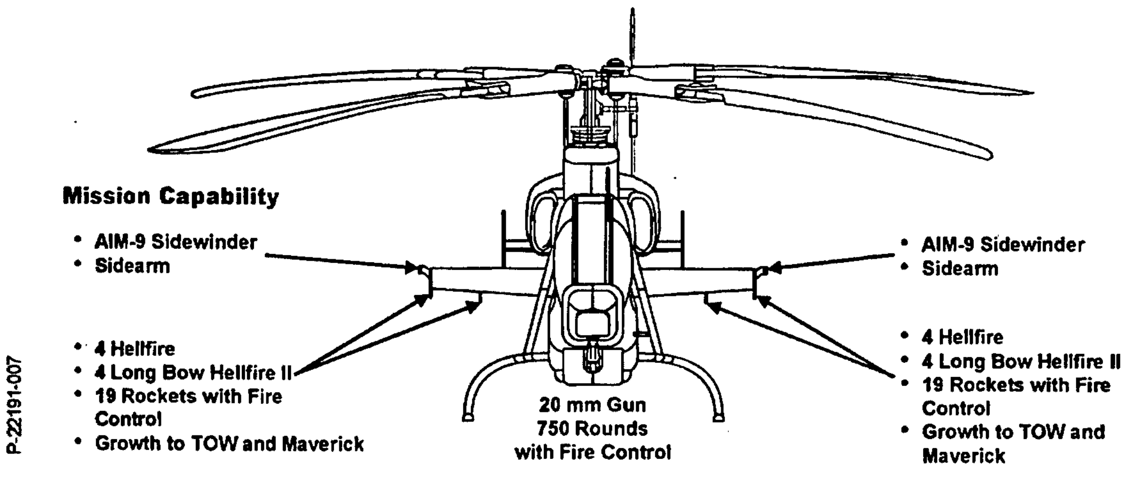


Figure 7. Widest Array of Ordnance of any Attack Helicopter

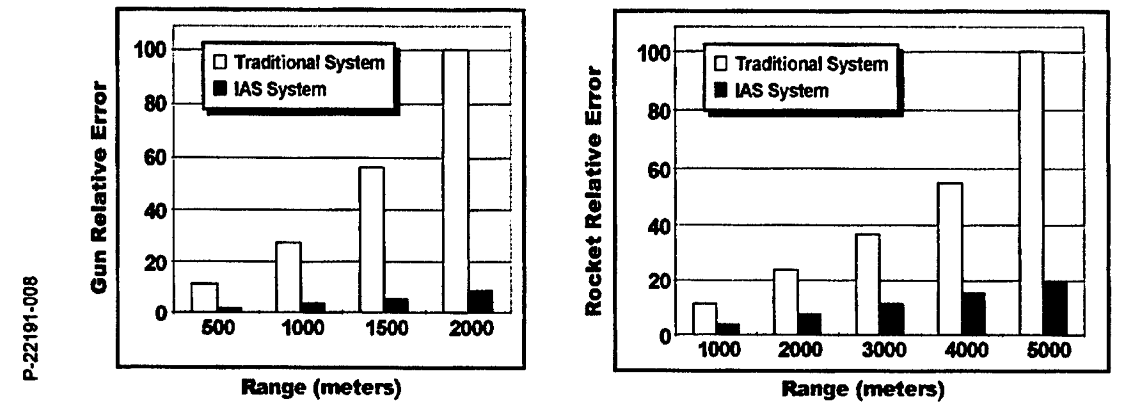


Figure 8. Relative Error Improvements with Integrated Avionics Systems

THE TOTAL INTEGRATED AVIONIC SYSTEM

Maximum commonality of product across platforms; achievement of redundancy and backups in all critical areas of processing, displays, and essential sensors; massive reserves of processing and bus bandwidths are delivered within the Integrated Avionics System. Figure 9 shows the total complement of components and architecture for the AH-1Z, in concept form. Figure 10 shows a more accurate depiction of the relative architecture of the AH-1Z and UH-1Y. It also clarifies the degree of component and architectural commonality, as well as showing the degree of redundancy provided to achieve high probabilities of mission success. Beyond those items of displays, sensors and weaponry previously discussed, are the elements which support other key functions. These include:

Communications: based upon the new U.S. Navy standard RT-1794 integrated radio, combines UHF/VHF, COMSEC, and modem into a single unit. For the UH-1Y is further added the expansion to SATCOM in support of its combat coordination and information transfer role. Both aircraft are provided new tactical data communications capability created within the centralized Mission Computer to generate, receive, and exploit digital messages and imagery in accordance with the new standards of Variable Message Format (VMF) standards.

Navigation: is primarily achieved with the U.S. Navy Embedded GPS Inertial (EGI) and air data subsystem, which in the case of the AH-1Z is a low airspeed subsystem necessary to support weapons delivery in hover or at near zero speed. Backup sensors and displays are provided in the event of a total IAS failure. A modern, U.S. Navy standard digital map system is provided supplying full capability for Digital Terrain Elevation Data (DTED) and Compressed Arc Digitized Raster Graphics (CADRG). It also is used as a navigator map display source, as a threat visibility indicator, and is part of the in-flight mission planning mode.

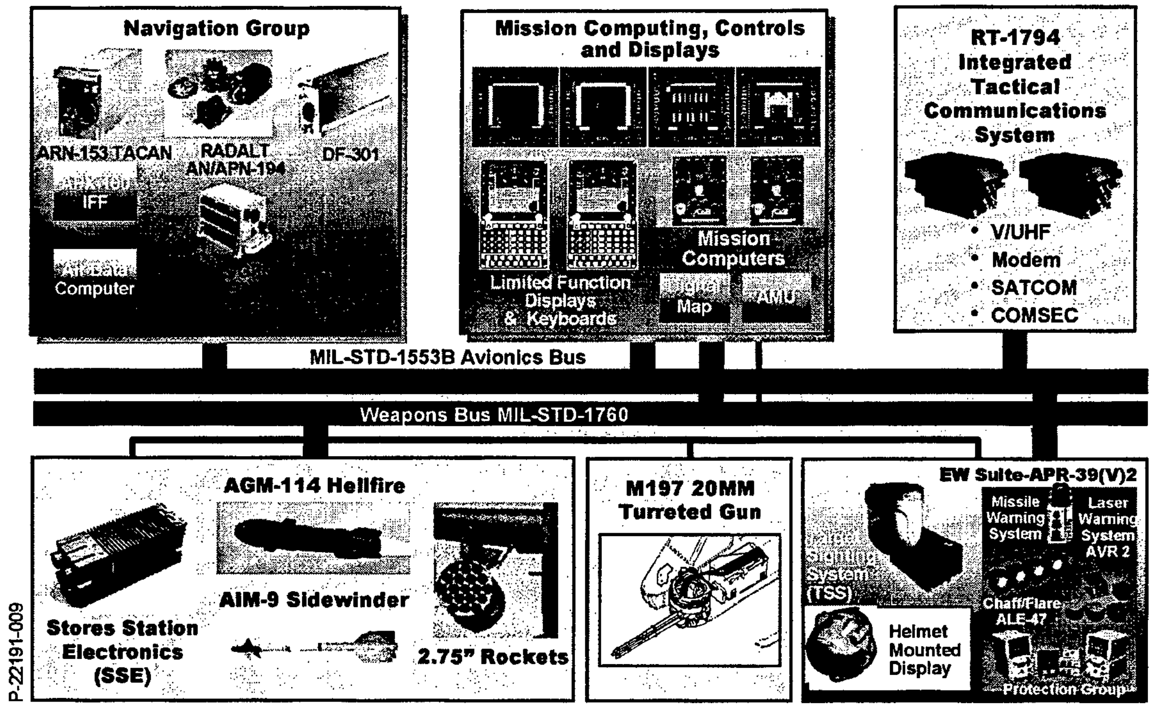


Figure 9. AH-1Z Integrated Avionics System Components and Architecture

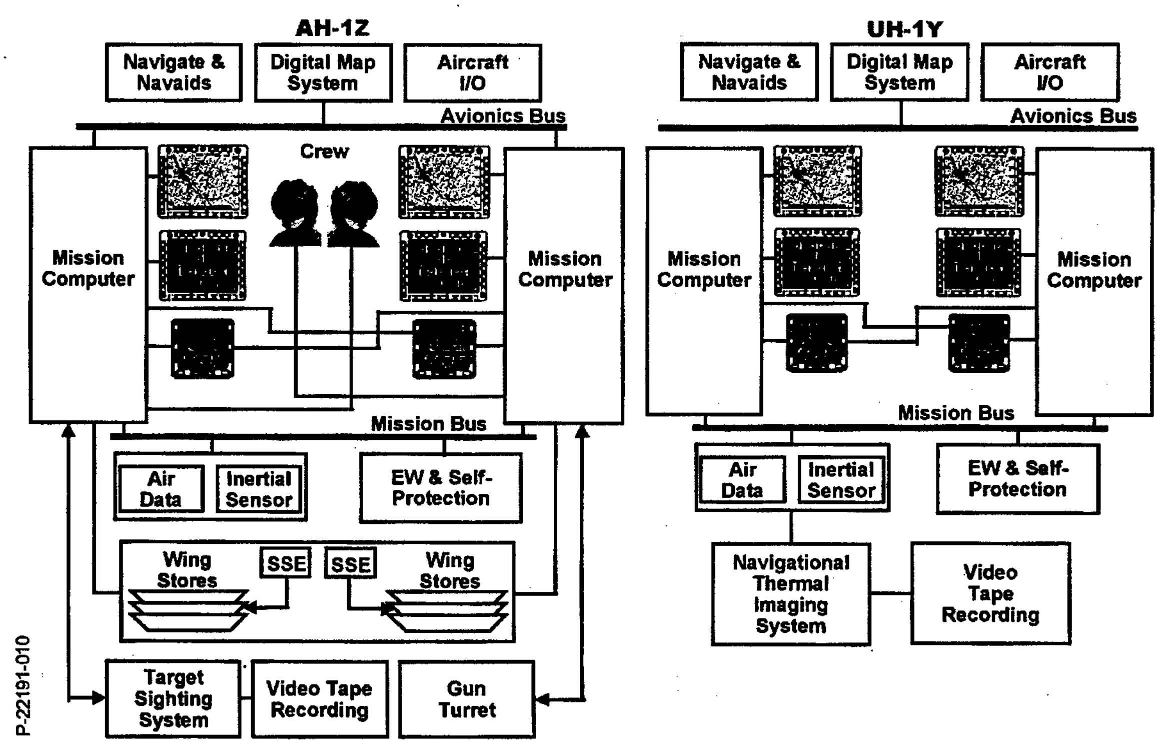


Figure 10. Comparison of AH-1Z and UH-1Y Avionics Architecture

EW/Self-Protection: consists of Litton Applied Technology Division's (ATD) APR-39. The APR-39 is upgraded to provide full MIL-STD-1553B access of threat warning. It also displays data to the Mission Computer, thus allowing optimal integration of threat situational awareness. The ALE-47 chaff and flare dispensing subsystem is provided, together with the AAR-47 missile warning and AVR-2A laser detector.

ADVANCED OPEN ARCHITECTURE MISSION COMPUTER

Mission Computer Requirements and Design Decisions

In keeping with the overall avionics objectives for mission versatility, low cost of ownership and performance to satisfy the needs of situational awareness in a Network Centric Mission, it has been necessary to develop a new advanced Open Architecture Mission Computer incorporating the following important design points: 1) The need to deliver enormous capacity for processor throughput, memory and internal communication bandwidth, all of which is essential in accommodating the demands of information superiority. 2) This computer will be at the core of functional upgrades over the next 25 years, and must come equipped with provisioned spare capacity and be able to accept future module insertion. 3) The ability to install third party modules requires that open architecture standards for mechanical form factor and backplane electrical interfaces be included.

Interpreting these requirements into a design mechanization was undertaken by realizing that the following be included:

- Maximum exploitation of Advanced Commercial Componentry is essential to yield high functional density, and hence performance margins. This in turn interprets into the need for sophisticated thermal management.
- Selection of the ANSI VITA Standards for 6U VME mechanical form factor and backplane connection. Shortcomings found in catalog solutions have been overcome through architectural expansion, while maintaining compliance to standards.
- Designs of modular subfunctions which could build whole functions at the plug-in module level. This not only achieves lower cost of ownership and lower design cost, but also address the major VME shortcoming of interconnection bus bandwidth.

Exploitation of Commercial Componentry

Revolutionary gains in commercial electronics have occurred which makes possible advanced avionics performance. These are evident in all of the functions for mission computers with general-purpose processor throughput, memory density, graphics processing and digital video manipulation at the forefront. In each of these areas, the improvements in capability, whether measured in throughput; polygons per second; texture pixels per second or megabits per device; essentially double every 18 months. With few exceptions the component technology source for a general-purpose avionics Mission Computer is derived from the PC (personal computer) marketplace. The performance expectations in terms of processing power, graphics rendering and even power/volume are perfectly matched. For military applications these commercial solutions are essential, and lead to a challenging thermal management problem. Gone are the days when the military marketplace could specify and obtain advanced components operating from -55°C to +125°C. Today it is necessary to tailor the environment around the commercial device whose performance is likely to be in the range of -20°C to +80°C. This tailored environment still must withstand installation in aircraft and environmental exposures, which are extreme in all regards, including external temperatures from -55°C to +71°C. To add to this thermal challenge is the fact that the more advanced IC components from the commercial marketplace are packaged to dissipate heat from the top cover of the device, not the mounting base, making the traditional "Core Heat Sink" module design imperfect. This new Mission Computer uses a combination of processes and design features to solve this problem:

- Component rescreening and analysis of IC foundry techniques, which ensure that a device will operate reliably beyond its advertised commercial temperature, range.
- Selective use of high thermally conductive encapsulated composite fibers, which can be applied to high value, high power dissipating parts to conduct heat efficiently to housing side-walls.
- Selective use of Thermo-Electric devices (Peltier junction) which can be allocated to selected components or component areas, and maintain a much narrower thermal swing.

6U VME Standards and Their Shortcomings

Although the PC internal processor and backplane interconnection is built upon a set of interface standards which includes PCI bus, ISA, etc., the accepted military standard for open architecture has become 6U VME which establishes a precise module mechanical form factor, backplane connector type, and interconnection bus. Deficiencies exist in each of these areas, but it does have the value of a large product base, and a well-maintained set of standards. The advanced Mission Computer provides installation capability for all third party 6U VME modules and provides full compliance to the ANSI VITA standards with its custom fitted modules. However, architectural and mechanization features are used to overcome the deficiencies found in catalog solutions. Specifically, these include:

- 6U VME baseline connectors are limited in allocation for backplane custom use. Specifically, the two 91-pin connectors are pre-allocated to VME_{64} bus and power, leaving only 60 user definable pins and is inadequate for efficient module partitioning. The Standards Committee has addressed this with extensions to an additional P-0 connector, and increases to a 4th and 5th row on the basic P-1 and P-2 connectors. This Mission Computer fully exploits this expansion.

- The basic 6U VME module is mechanically designed as a single sided heat sinked module and has two serious deficiencies: 1) with modern low profile components it is possible to create double-sided modules and double the capacity of function, and 2) that advanced commercial ICs need heat sinking from the top (not the base as is the case in the standard module). Most catalog solution address this by the installation of plug-on mezzanines, but their mechanical integrity is suspect in military environments, or the complexity of attachment structure diminishes the packaging footprint. This mission computer design uses a central core heat-sink, which accepts a two-sided PCB fitting, and adds custom top-heat-sink attachments for selective parts. All of this is accomplished in the standard width of 0.8 inch (2 cm), and is substantially more rugged and far more thermally efficient.
- Backplane bus bandwidth, more than any other aspect of the Mission Computer, provides for functional upgrade or limits its growth. In this regard, the 6U VME standard, even with the expansion to VME_{64}, is at the low end of capability. For this Mission Computer, the VME bus has been allocated only the task of global control and low bandwidth functional interconnect. No attempt is made to use this bus for such functions as Graphics Display List Management, Memory Access, or transfer of realtime digital data bases. In order to deliver both the functional interconnection bandwidth for the current avionics and to have convenient upgrade approach, the design strives to put "whole functions" on single plug-in modules so that the high bandwidth PCI bus can be linked without exiting into the backplane. In selective zones, the backplane is enhanced by careful addition of interconnection links using PCI bus, LVDS internal digital video and fiber channel external digital video.

This tailoring of backplane using "drop-on" flex-prints is part of an interconnection scheme that consists of a multi-layer PCB in which the 6U VME standard interconnect is equipped in copper etch, critical "tailored" buses use. "Drop-on" flex-prints and low bandwidth noncritical signals can be made with wire-wrap. In this way all of the flexibility for growth is given while compliance to standards is maintained.

Mixing and Matching With Modular Subfunctions

A careful partitioning of modular functions and sub-functions has been achieved which supports the need for bandwidth maintenance, thermal allocation and maximum reuse. Specifically a number of basic building blocks of high performance functions are designed which can be mixed by allocating to module sides (A-Side/B-Side). These include general purpose "standard host processor", graphics processor, input video multiplexer/digital converter, input/out functions, etc. This approach to backplane interconnects and subfunction tailoring is shown in Figure 11.

AH-1Z AND UH-1Y MISSION COMPUTER FEATURES

These principles of design have been applied to the AH-1Z and UH-1Y Mission Computers, realizing all of the global objectives for delivery of substantial performance, growth and upgrade flexibility and accommodation of third party modules through compliance to Open Architecture Standards. Figure 12 shows the module complement for AH-1Z Mission Computer, and the logical subset for UH-1Y. It shows that in a 14-module slot housing, 6 growth slots remain for AH-1Z and 11 growth slots for UH-1Y. Figure 12 also shows the two third-party supplier-provided 6U VME modules for the helmet subsystem. Most notably is shown the manner in which functional building blocks have been mixed to tailor whole functions at the module level. In the case of the AH-1Z the powerful "Standard Host Processor" has been used as an "A-Side" fitted subfunction to support four separate whole functions as Mission Processor, Graphics Processor, Weapons Processor, and VTR Symbology Processor.

A standard housing, air plenum/mount and power-supply is used for both AH-1Z and the depopulated UH-1Y. The enclosure, together with the internal module design features, provides a fully compliant solution to the need of MIL-STD-810C environment and to the electro-magnetic compatibility needs of MIL-STD-461/462. This is shown in Figure 13.

The equipped Mission Computer performance is summarized in Table 1. Major points to be noted:

- Delivery of 800 MIPs of processor throughput in AH-1Z
- 256 MB of main memory
- 8 equipped 1553B buses

Also a video and graphics subsystem is included, in which a single module can drive two simultaneous high resolution color screens, with realtime scene-generated graphics and video overlay/windowing. Against this fitted capability the baseline solution uses less than 20 percent of the throughput, less than 30 percent of the memory, and only 3 of the 8 fitted MIL-STD-1553B channels.

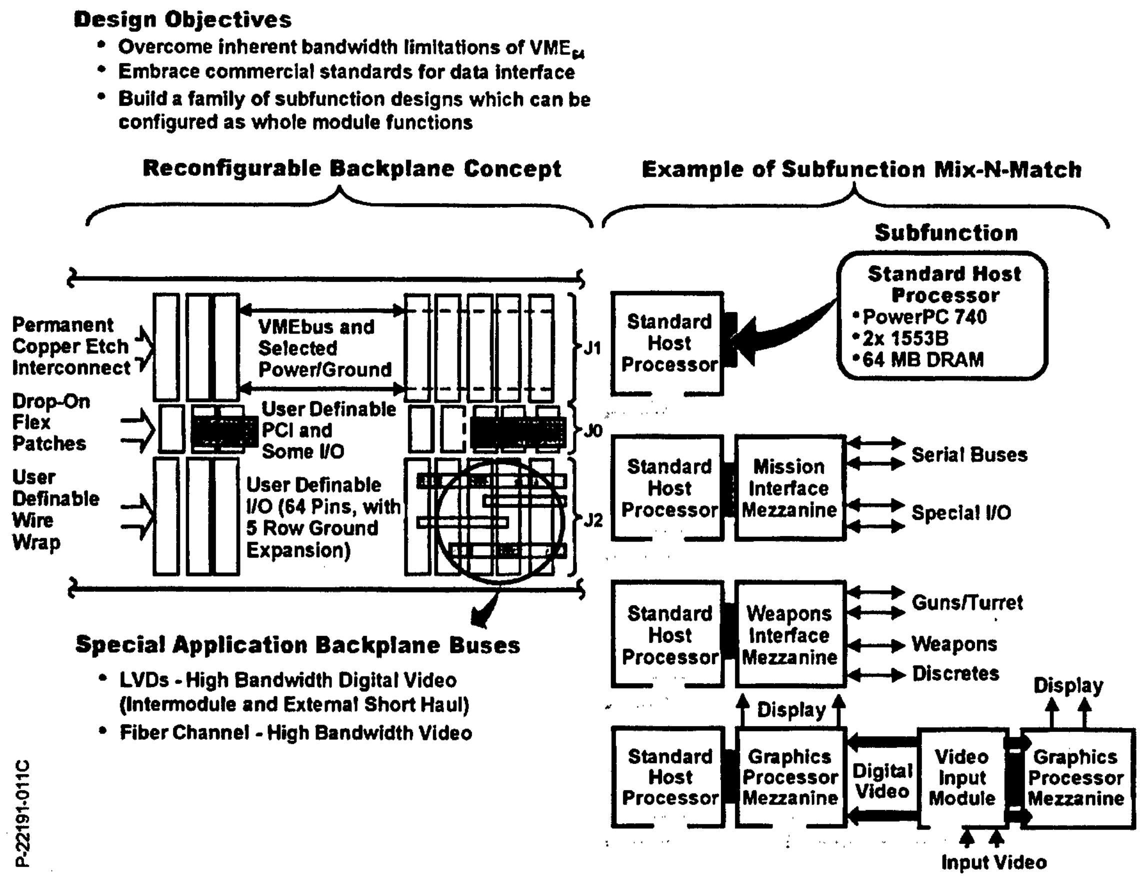


Figure 11. Mission Computer Concepts of Backplane Interconnection and Subfunction Mixing

CONCLUSION

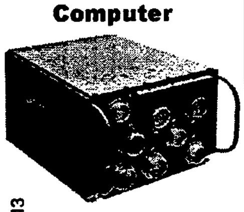
The H-1 IAS upgrade delivers the most modern and cost-effective suite of avionics available today, and addresses the mission needs of the next quarter century with full appreciation for growth and change. This adds to the benefits achieved in other areas of platform upgrade, providing to the U.S. Marine Corps essentially, a new fleet of helicopters for versatile Attack and Utility missions.

Side A	Side B		Module Content: AH-1Z Computer	Module Content: UH-1Y Computer
Standard Host Processor • PC603 (740) • PCI Bridge • 2 x 1553B • 512K Flash • 64 MB DRAM • 32K NOVRAM	**Mission Interface Mezzanine** • 7 x ARINC 429 (3 x Receiver/4 x Trans) • 2 x RS-422 • Force Stick I/O • VME Slave • 9 Discretes • 4 Output Discretes	= Mission Processor Module	1	1
Standard Host Processor • PC603 (740) • PCI Bridge • 2 x 1553B • 512K Flash • 64 MB DRAM • 32K NOVRAM	**Graphics Processor Mezzanine** • 3D Lab 500 MX/Gamma • 2 x Fiber Channel Graphics Outputs (1024x768) • 2 Output Frame Buffers	= Graphics Processor Module	1	1
Video Capture Processor • 12 Reconfigurable Composite Video Inputs • Zoom; De-Interface; Capture	**Graphics Processor Mezzanine** • 3D Lab 500 MX/Gamma • 2 x Fiber Channel Graphics Outputs (1024x768) • 2 Output Frame Buffers	= Video Processor Module	1	1
Standard Host Processor • PC603 (740) • PCI Bridge • 2 x 1553B • 512K Flash • 64 MB DRAM • 32K NOVRAM	**Weapons Interface Mezzanine** • Full Digital Gun Loop • I/O to SSE • 28 Input Discretes • 24 Output Discretes	= Weapons Processor Module	1	N/A
Standard Host Processor • PC603 (740) • PCI Bridge • 2 x 1553B • 512K Flash • 64 MB DRAM • 32K NOVRAM	**Helmet Processor Mezzanine** • Adapted Form Graphics Processor Mezzanine • LVDS Graphics Output • RS-170 Graphics Output	= VTR Symbology Module	1	N/A
HMD Interface • Calculate Distortion Correction • Drivers/Creates CRT Ramps • 2 Channels/Module	**Camera Electronics Mezzanine** • Capture and Processes Camera Video • 2 Channels per Module	= HMD Processor Module	1	N/A
Helmet Tracking Module	Supplier Provided 6U VME Module	= Helmet Tracking Module	1	N/A
Helmet Deflection Module	Supplier Provided 6U VME Module	= Helmet Deflection Module	1	N/A
		Available Spare Slots	6	11

P-22191-012A

Figure 12. AH-1/UH-1 Module Combinations

Mission Computer



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Characteristic	AH-1Z	UH-1N
Size	15.47 in. (L) x 11.5 in. (W) x 8 in. (H)	15.47 in. (L) x 11.5 in. (W) x 8 in. (H)
Weight	35.5 lb	24.5 lb
Power (28V) (AC)	313 watts 80 watts	110 watts 80 watts
Reliability	1303 hr MTBF	3693 hr MTBF
Maintainability	99% BIT Detection 98% Isolation to WRA	99% BIT Detection 98% Isolation to WRA

- Environmental Qualification Tests to MIL-STD-810E
  - Temperature/Altitude
  - Humidity
  - Fungus
  - Salt Fog
  - Sand and Dust
  - Explosive Test
  - Vibration
  - Shock
- EMC Testing to MIL-STD-462

Figure 13. Comparison of AH-1Z and UH-1Y Mission Computers

Table 1. Mission Computer Performance Summary

		AH-1Z	UH-1Y
Physical			
Housing Characteristics		Full ATR/15.5" Long	Full ATR/15.5" Long
Module Format		6U VME (+Connector Ext)	6U VME (+Connector Ext)
Cooling (Housing Level)		Fan Forced Air	Fan Forced Air
Cooling (Module)		Conduction	Conduction
Backplane Interconnect		Copper Etch + Custom Zones	Copper Etch + Custom Zones
Front Panel Attachment		Re-configurable Flex + Filters	Re-configurable Flex + Filters
Total 5 Lots (Provisioned/Used)		14/8 (6 Spare)	14/8 (11 Spare)
Functional			
General Purpose Processing (Standard Host Processor)	Frequency/Throughput	4 x (200 MHz/200 MIPS) = 800 MIPS	2 x (200 MHz/200 MIPS) = 400 MIPS
	Main Memory	4 x [64 MB (128M Avail)] = 256 MB	2 x [64 MB (128M Avail)] = 128 MB
	Boot/NOVRAM	4 x [512 KB/32 KB] = 2048 KB/128 KB	2 x [512 KB/32 KB] = 1024 KB/128 KB
	PCI Bridge	Equipped Each Module	Equipped Each Module
Video Graphics Subsystem (Graphics Processor/ Video Capture)	Graphics Outputs (Digital)	4 x [1024 x 768 Full Color] Reconfigurable	4 x [1024 x 768 Full Color] Reconfigurable
	Input Video	12 Reconfigurable Channels	12 Reconfigurable Channels
	Video/Graphics	Zoom; De-Interlace; Window in Window Overlay	
	Graphics Features	Anti-Alias; Alpha Blend; Polygons & Textures; Freeze Frame	
Weapons Subsystem	Guns (20 mm)	Full Digital Gun Control Loop	N/A
	Missiles/Rockets	Control of SSE (Software)	N/A
General Input/Output	1553B	8 Equipped (3 Assigned)	4 Equipped (3 Assigned)
	ARINC 429	3 Receivers/4 Transmitters	3 Receivers/4 Transmitters
	RS-422/RS-237	4 x 4 RS-422	2 x 4 RS-422
	Discretes In/Out	47 x Inputs/28 x Outputs	19 x Inputs/4 x Outputs
	Other Serial	Fiber Channel/Ethernet	Fiber Channel/Ethernet
	Graphics Creation	All HMD Symbology	N/A
Helmet Display Subsystem	CRT Drive	Deflection & Distortion Correction	N/A
	Night Pilotage Cameras	Camera Processing/Overlay	N/A
	Head Track On	Processing & Calibration	N/A

STRATEGY FOR LONG-TERM SYSTEMS AND TECHNOLOGY ADVANCEMENT

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ABSTRACT

Many challenges have emerged within the past five years for both military customers, as they plan for and purchase aircraft, and for manufacturers, in producing these aircraft. Opportunities to develop new models of military rotorcraft have decreased with steady reductions in military budgets and the post cold-war environment. These budget reductions, coupled with quantum advances in computing technologies that have advanced ground-based and airborne processing power, have shifted the focus of military customers from new model development to increased aircraft performance via system upgrades and training.

The emphasis on meeting long-term operational needs with these upgraded systems and the training required to optimize their use has resulted in an imperative to change acquisition and implementation strategies for both the aircraft customer and the prime manufacturer. This paper focuses on the impact of these strategies on the rotorcraft industry, as follows:

Systems Engineering. The architecture of aircraft mission equipment packages must be carefully planned in order to provide the capability of rapid and cost-effective modifications and upgrades. Avionics architectures have long supported highly federated mission processing furnished by suppliers with highly proprietary technical solutions. These complex closed subsystems cannot be modified or upgraded without considerable expense, and soliciting equivalent functionality from other suppliers is cost-prohibitive. Re-engineering the supply chain process, scrutinizing avionics make-buy decisions, and concentrating systems engineering activities early in development programs can aid in satisfactorily and predictably meeting the long-term operational needs of both the military customer and the manufacturer.

Aircraft-level integration facilities. Ground-based systems integration solutions must supplant aircraft testing to the maximum practicable extent in order to accommodate rapid and economical test results without expending valuable aircraft time. Systems integration test stations that combine aircraft subsystems with subsystem emulations, math model simulation, and playback capability can provide a high degree of fidelity to on-ground testing, both prior to first flight and during the aircraft flight test program.

Training systems. Training for pilots, crews, and maintainers must move to improved on-ground training systems, such as full flight simulation trainers and non-motion cockpit trainers. In order to make the rapid changes required to keep trainers current with fielded aircraft, these trainers must also be developed utilizing a concept of optimizing open systems architectures and commercial off-the-shelf hardware and software. With fewer aircraft being purchased and more complex mission equipment in development, on-ground training solutions can provide aircraft personnel tools for becoming familiar and proficient with their tasks off the aircraft.

INTRODUCTION

Today's military customer wants

- An affordable airplane
- That meets performance requirements now,
- Has incremental performance upgrades planned that are affordable and schedule-efficient, and that also
- Has training for crew and maintainers that is concurrent and economical.

Some of the processes that can be utilized to maximize the ability to satisfy customer requirements are

1. Strong systems engineering focus at the inception of upgrade program planning that provides specific and quantifiable performance requirements such that the mission equipment package architecture and top-level requirements can be allocated to subsystems very early in the program.
2. Robust aircraft-level systems integration testing to eliminate common problems that can be resolved prior to first flight, to provide confidence that aircraft subsystems are interacting correctly and predictably prior to aircraft installation, and to support identification and resolution of problems after the aircraft has been fielded.

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

3. Training devices, including engineering simulation and flight training devices with and without motion. These trainers provide familiarization with the aircraft that can be performed prior to aircraft fielding, and reduce costs associated with utilization of the aircraft itself.

SYSTEMS ENGINEERING PROCESS

Every aircraft manufacturer has a long history in cockpit development programs and projects that have failed because their systems engineering was not sufficient to specify and allocate requirements that would meet the military customer's short- and long-term needs. For this systems engineering process to be successful requires communication between customer and aircraft manufacturer very early in the aircraft conception period, an orderly and disciplined formulation of mission equipment architecture and expected function, intelligent competitive procurement, and strong technical oversight following the procurement period from both the customer and the aircraft manufacturer.

It is difficult to assess the success of the systems engineering process, because the program must be concluded prior to being able to measure the results of the effort. This means that successful systems engineering requires an up-front investment in cost and schedule—which mandates trust and commitment by both the customer and aircraft manufacturer, with no guarantee of success. Bell Helicopter Textron Inc. has participated in many aircraft and systems upgrade programs—with varying levels of success.

At the completion of any aircraft development or upgrade activity, a systematic review should be undertaken to provide insight into the management of subsequent programs:

- How producible are the subsystems?
- How does the modified aircraft cockpit reduce crew and maintainer workload?
- How easily modified are the cockpit systems from this point forward?
- How capable are the subsystem suppliers in repeating previous success?
- How have the subsystem suppliers addressed technology obsolescence?

This review cannot take place until the mission equipment package has been deployed for a time period sufficient for early box failures and customer evaluation to have taken place, and by that time, most aircraft manufacturers are committed to other development programs.

As the benefits of systems engineering have become evident, Bell has developed some guidelines, with the aid of internal investments in process and product improvements, that, over the past three years, have yielded positive results in expertise and in potential repeatability of success.

Improvements have been made in the following three areas:

- Mission Equipment Package planning
- IR&D involvement for future benefits in systems engineering, in particular
    1. Process improvements
    2. Product development knowledge
- Supplier selection

Mission Equipment Package Planning

In the area of Mission Equipment Package planning, technical and management involvement with the customer to understand and clarify a near- and long-term vision for the aircraft upgrade has been highly successful. On the H-1 Upgrade program, Bell and NAVAIR set up complementary team structures within each of their organizations, called Integrated Product Teams, which conducted trade studies to determine the optimal mission equipment package to meet customer desires while fitting into their funding profile. This structure was assembled prior to any avionics supplier selection and allowed aircraft requirements to be logically allocated to subsystems along with targets for weight, cost, reliability, and maintainability.

Bell employs this methodology on other cockpit development programs for the military, as well as on commercial programs, where Bell considers the Federal Aviation Authority (FAA) to be the customer. Forming a working team, consisting of management and technical contributors, early in the program allows the mission equipment package architecture to be defined and decisions made such as federated versus distributed subsystems, make versus buy, and subsystem vendors, and culminates in a program-level Preliminary Design Review. This Preliminary Design Review signifies the time at which all requirements are understood by the airframe manufacturer and subsystem suppliers, and at which the customer understands the limitations of the manufacturer and supplier solutions. At this point, there should be confidence, if the systems engineering process has been employed well, that the probability of successful implementation on the aircraft is high.

This process has worked well on the H–1 Upgrade Program, as well as the V–22 program and its variants, also deliverable to the U.S. Navy and Marines. On the H–1 Upgrade Program, robust systems engineering led to the selection of Litton as the major cockpit system supplier, with ancillary suppliers for other airborne systems. In addition, informed trade studies resulted in the Bell in-house development of the H–1 Flight Control System (FCS) and two types of interface processing units, called Wiring and Integration Remote Terminals (WIRT).

As a more detailed example of proficient systems engineering with long-term supportability, the H–1 Upgrade Program FCS is identical for both UH–1Y and AH–1Z aircraft, and needs only two card types to meet its functional specifications: a CPU card and an axis card. The current customer requirement for a three-axis system uses one CPU card and three identical axis cards, and a fourth (with accompanying power supply) can be added into the spare card slot if a fourth axis is funded by the customer in future. The design of these subsystems within Bell were leveraged from an on-going IR&D project, which is detailed in the following section.

IR&D involvement for future benefits in systems engineering

Bell, since 1995, has focused a portion of its internal research and development (IR&D) funding on improvements in systems engineering, specifically in areas of process improvement and in product development knowledge.

Process improvements. Two sets of activities have raised awareness and increased the knowledge base within Bell of our internal systems engineering processes, and have provided a framework for improving the aircraft mission equipment development process on future programs. These investments have yielded excellent results, as described below:

1. Independent capability assessments via the Carnegie Mellon Software Engineering Institute (SEI) Software Capability Maturity Model, both for technical oversight of suppliers and for in-house software development efforts. The entire Systems Integration organization at Bell was assessed in August 1996 at a high Level 1 (Initial), and reassessed in October 1997 at Level 2 (Repeatable), both times by an independent consulting agency. The Systems Integration organization, which includes all system design areas (avionics, armament, electronic warfare, flight controls, and electrical systems) and hardware, software, and test design capability for these systems, expects to achieve Level 3 (Managed) at their next assessment scheduled for August 1999. This commitment to improve internal processes and to actively seek objective assessments of these processes has driven Bell to make their systems and software processes and the technical management of their avionics system suppliers consistent between projects and has provided guidelines for training the engineering staff.

2. Benchmarking activities were conducted in 1998 by a Design & Producibility Team, staffed with Engineering and Manufacturing personnel tasked with evaluating the development process in the industry, as it existed in key companies. This team conducted benchmarking throughout aerospace and related industries to identify "best in class" practices to be adopted at Bell for reducing schedule and cost in aircraft development and upgrade programs. This benchmarking activity has resulted in the formulation of a development template for measured and concurrent product development and upgrades which tie all responsible functional areas together to reduce traditional schedule and cost impacts. This template will be utilized to predict future program costs based upon historical data, and will increase the repeatability of success on subsequent programs.

Product development knowledge. The Advanced Systems and Technology Integration (ASTI) program was initiated in 1996, in part to provide insight into the use of a generic avionics architecture, and to provide a series of prototype hardware and software components that can be easily migrated into flightworthy components. The goals of this IR&D program were twofold: to keep in-house development capabilities current with technology, and to make Bell engineering "smart managers" in the area of technical supplier oversight for complex airborne systems.

There were three main areas of avionics hardware and software investigated: data acquisition systems, instrument display systems, and mission computers. Within each of these areas the following topics were examined: use of commercial off-the-shelf (COTS) hardware and software components, improved system and software development toolsets, and open system architectures. The efforts of the ASTI program have thus far resulted in the following accomplishments:

1. Dual use (for both military and commercial applications) data acquisition system hardware and software using COTS components.

2. Generic object-oriented display software components for design, evaluation, and real-time use in instrument display systems.

3. Increased awareness of the advantages of open system architectures.

Recent focus by the military on the reduction of development costs, the increased use of commercial off-the-shelf (COTS) parts and processes, the use of improved system and software processes, and the design of open system architectures, has resulted in changes in the subsystem development process. The COTS label encompasses more than using industry standard components; it also entails using industry standard systems, processes, and tools. Improved software processes and toolsets focus on increased software reuse, maintainability, and customer satisfaction, using open system architecture as the foundation for facilitating these initiatives.

Integrating COTS components into military designs requires determining how to modify a military design to use COTS components as well as how to modify the COTS components to work in a military design. Thus far, the use of COTS in the military has mostly been at the component level.[1] However, there is much more to be gained if industry standard systems, processes, and tools can be employed as well. An example of using industry standard tools might be the choice of C, C++, or Pascal compilers as opposed to past military standards such as Jovial or Ada. Another, potentially much more beneficial, approach to integrating COTS components is the concept of dual use. Dual use is the idea of developing systems that can be used in both commercial and military applications, thus attaining the benefits of coproduction. The benefits of using COTS components and systems in military products must be carefully weighed against compromising essential military specific requirements.

Open system architecture "is an architectural framework defined by Open Systems interface standards. Open Systems standard interfaces are clearly and completely defined interfaces that support interoperability, portability, and scalability."[2] The application of open system interface standards should be an integral part of the design process. Although using standard interfaces is the key to designing successful open system architectures, the selection of interface/firewall locations is also important. Selecting appropriate interface points in the system may allow subsystem and/or component reuse and/or upgrade with relative ease. The personal computer market is an extraordinary example of how open system architectures can lead to efficient development of new products.

The Bell-funded ASTI program identified COTS, system/software process, and open system architecture topics and investigated their application to helicopter avionics components:

Data Acquisition Systems. The data acquisition unit (DAU) is a system that is connected to a variety of sensors and/or discretes for data collection. Each analog input is digitized through an analog-to-digital (A/D) converter, and then output for display or further processing using either a MIL-STD-1553 or ARINC 429 data bus. Likewise, each discrete input is either acted upon internally or passed on for display or further processing. The DAU can also provide several ancillary functions, such as storing system exceedences and stick shaking.

Several COTS options were investigated for use in the DAU. As is common, the main use of COTS was at the component level. All A/D, D/A, and processor cards were designed using COTS components, where possible. Various COTS input/output (I/O) boards were considered; however, none had the necessary channel capacity. Likewise, COTS processor cards were considered, but the unit cost for them was typically too high. The system's power supply was a selection from industry standard off-the-shelf components. In conjunction with DAU development, several industry standard off-the-shelf sensors (such as temperature bulbs, strain gauge pressure transducers, and chip detectors) were identified and implemented across multiple platforms.
During the process of DAU development, multiple industry standard processes and tools were used. Following is a sample listing of tools and their use:

- DOORS© – System requirements management and traceability.
- VIEWlogic® – Hardware schematic design.
- PADS© – Hardware trace routing.
- Green Hills© C – Software development environment.
- LDRA© – Software testing.
- PVCS© – Configuration management.

Many open architecture ideas were also investigated during development of the DAU. The chassis was designed for standard VME 6U form factor cards. A standard VME backplane was investigated; however, the VME standard did not provide the necessary undedicated I/O lines for sensor input. The VME 6U form factor card

[1] Nordwall, Bruce D., "Buying Off-the-Shelf Challenges Military," *Aviation Week and Space Technology*, Vol. 146, (18):57–59, April 28, 1997.

[2] Roark, Chuck and Kiczuk, Bill, "Open Systems – a process for achieving affordability," *IEEE Aerospace and Electronics Systems Magazine*, Vol 12, February 2, 1997, pp 26–32.

size was chosen to allow inclusion of other existing VME 6U boards into the chassis if desired at a later point. The DAU was designed with two data output interface protocols: ARINC 429 and MIL-STD-1553. This has allowed dual use of the design for commercial and military projects.

The investigation into a data acquisition system has been a tremendous success. It has resulted in the DAU's inclusion in the current H–1 Upgrade Program, in the form of the Flight Control System (FCS), as well as two types of WIRT units, which serve as electronic interface units that process a variety of discrete and analog sensor inputs throughout the airplane. A variation of the DAU has also been used in the commercial Bell-Agusta Model 609 tiltrotor program, as the Ice Protection Control System. The risk reduction benefit of the ASTI program has ensured qualified H–1 FCS and WIRT units prior to scheduled aircraft needs within cost targets. Fig. 1 shows the DAU system architecture as defined on the ASTI program, with generic serial bus interface capability for dual use.

Instrument Display Systems. The instrument display system (IDS) is a system that graphically displays digital and analog engine, transmission, electrical, outside air temperature, clock, and fuel system information, formerly displayed on multiple analog gauges. It also provides an interface for data entry related to various ship configuration and flight parameters, such as fuel tank configuration and weight distribution, as well as a maintenance mode interface to access stored engine parameters and engine exceedence information. Fig. 2 depicts the system architecture for the IDS.

The digital flat panel display also allows the use of multiple colors to indicate normal, caution, and danger ranges. Fig. 3 shows a sample IDS display in black and white. The IDS engineering evaluation unit created during the ASTI investigation was developed almost entirely from COTS components. DY4© VME-based CPU and graphics cards were used to generate the graphical objects, simulate the input signals, and simulate the MIL-STD-1553/ARINC 429 interface. Two Sharp© flat panel displays were used to display the sample IDS screens, and WindRiver©'s VxWorks® real-time operating system was used to isolate the developed software from the hardware. Several other COTS products, including a Radstone© CPU board, were also evaluated as alternatives to the above configuration as part of the ASTI program.

During IDS exploration and development, several industry standard processes and tools were evaluated. One of the main tools explored was Virtual Prototype©'s VAPS® product, which allows quick creation and demonstration of display screens.

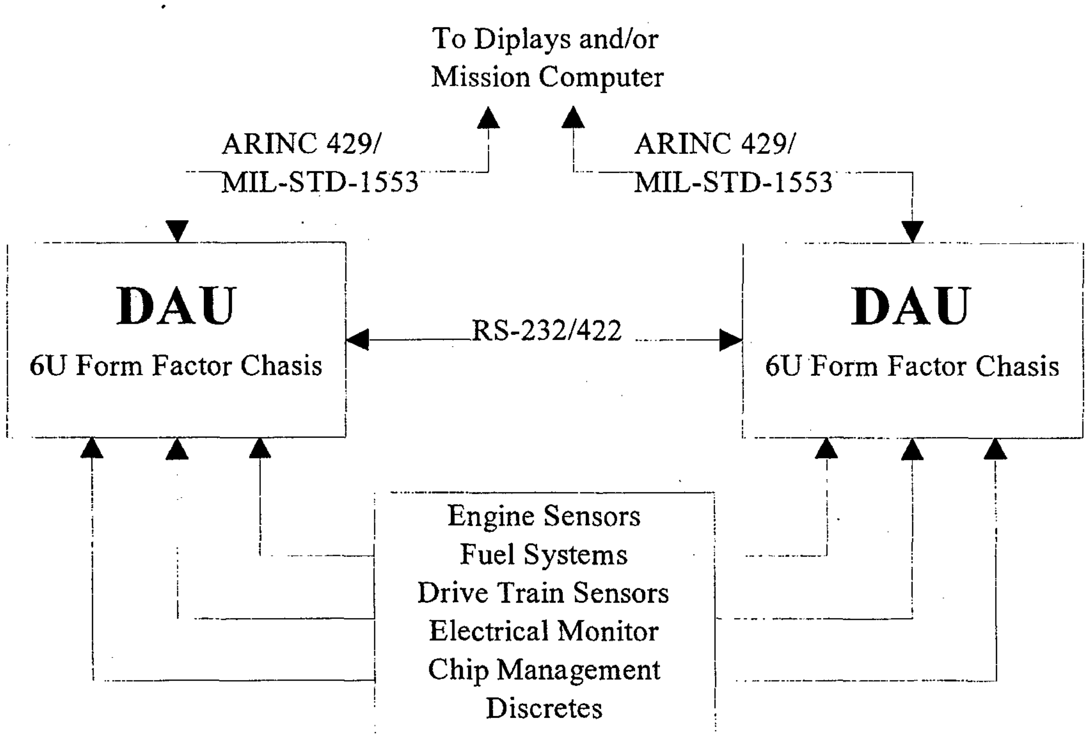

Fig. 1. DAU system architecture.

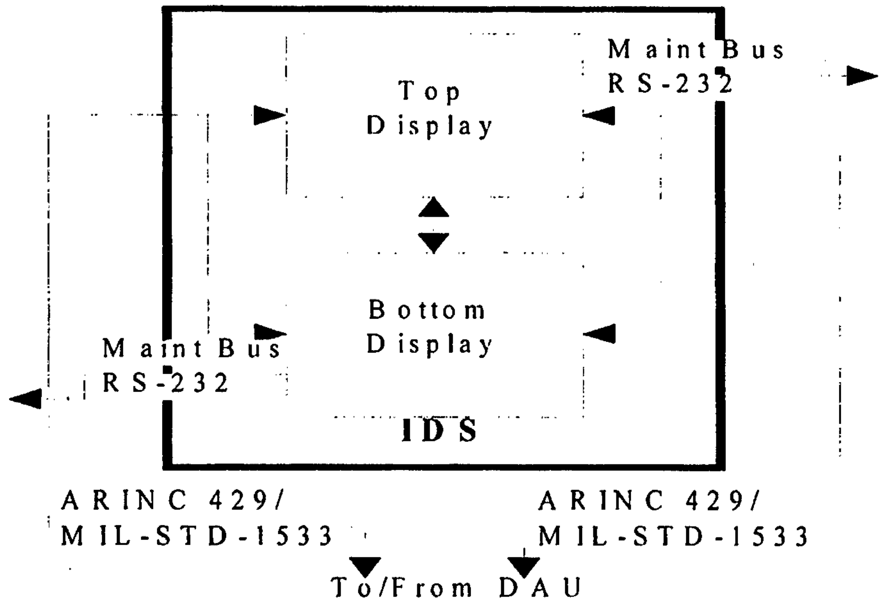

Fig. 2. IDS system architecture.

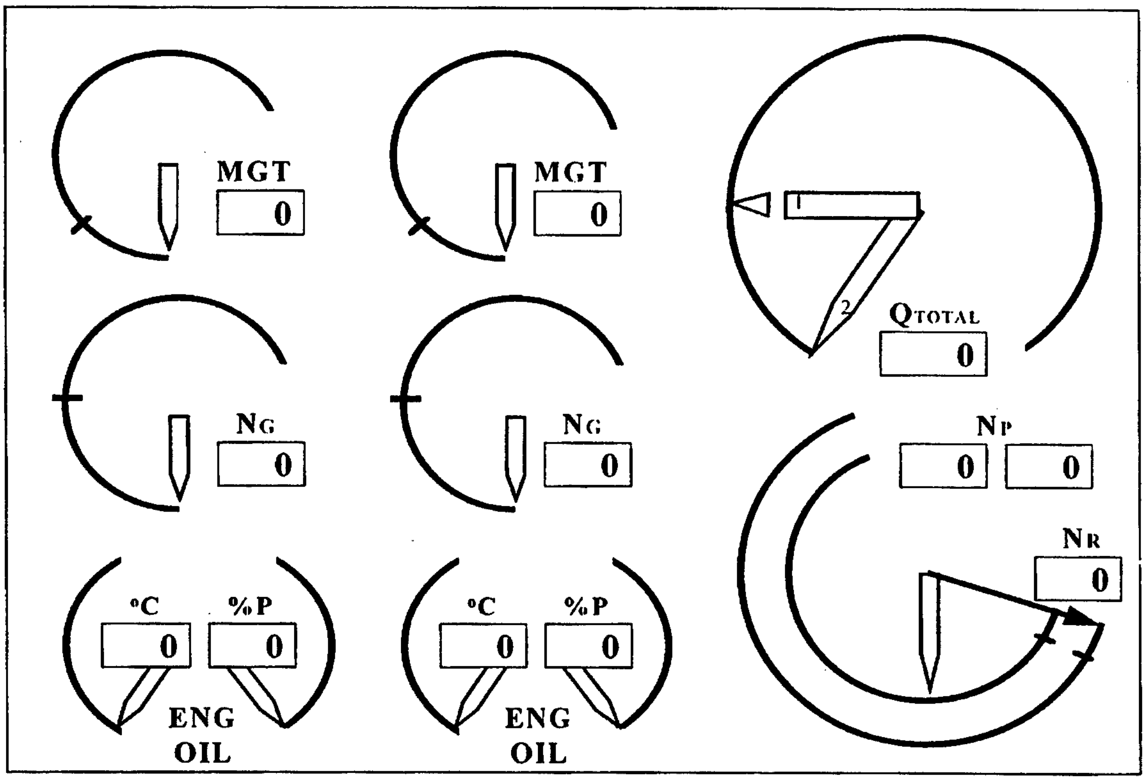

Fig. 3. Sample IDS display.

VAPS® provides a graphical user interface (GUI) that permits point-and-click design and demonstration of potential IDS display formats. It also provides a tool to convert the display formats into C-code that can then be compiled and executed on many different target systems. One of the ASTI program's goals was to successfully port the generated C-code into the real-time hardware, and use it to generate and update the displays in real time. During this process, several problems related to porting the C-code to the DY4© platform were encountered. But with help from Virtual Prototypes© and DY4© support personnel, the problems were quickly overcome. However, the final determination was that the update rate of the VAPS®-generated code was too slow to be directly applied on the selected hardware platform, and that validation and certification of the generated code might be difficult.

Once the VAPS®-generated code was deemed unusable for real-time use on the selected hardware platform, a library of C++ objects was developed to allow easy generation of IDS display formats in real-time software. The Bell Avionics Prototyping and Real-time Software (BARS) library contains objects to display any of the following instrument types at any position, rotation, or size:

- Dial – Standard circular, or partially circular, instruments with user defined indicators.
- Text – Digital readouts.
- Ribbon – Vertical bar that indicates the current value by its height.
- Warning/Caution/Advisory – Matrix of cells that display system messages.
- Tape – Horizontal region that can be used to display current heading information.
- Ruler – Vertical or horizontal "ruler" with an indicator pointing to the current value.
- Attitude – Attitude indicator.

The same IDS displays were recreated using the BARS library, and the hardware was easily able to achieve the desired update rate. The BARS software was designed using a layered approach in order to ease the transition between hardware platforms. All BARS graphical commands are based on the industry standard graphical language called OpenGL®. Certain hardware vendors may supply an OpenGL library; those that don't would require modification of an existing library to allow interfacing into their unique vendor software.

Open architecture concepts were used at the system level, such that any COTS display that can be programmed with C++ (or C with some BARS modifications) and that provides an ARINC 429 interface is a viable option for use in this architecture. In fact, the process of rehosting the software into a new graphical hardware system was demonstrated using the Radstone© hardware. Another method used to keep the architecture open was the use of OpenGL in the layered software design previously described. OpenGL is increasingly supported by vendors, so the need for the user to create an OpenGL interface for each new display unit should diminish.

The results of the IDS exploration include a software library toolset that can easily be used to generate IDS displays and can easily be ported to new hardware platforms, a standard interface into display systems, and a list of potential vendors for such display systems.

Mission Computer. A generic definition of a "mission computer" is a system that coordinates and disseminates information. It is responsible for requesting information from data collection systems (such as the DAU), possibly altering the information in some manner, and then sending that information to other systems.

The COTS options explored on the ASTI program were very similar to those explored in the DAU and IDS efforts. An off-the-shelf VME chassis was selected due to industry-wide acceptance. There are numerous vendors that provide CPU and communication cards for the VME chassis. In order to isolate the software from the hardware, WindRiver©'s VxWorks® real-time operating system was used. The use of an operating system allowed the interchange of CPU and communication cards from different vendors.

Improved system and software processes learned on the ASTI program will provide additional benefits to mission computer development in the future. The use of defined processes, with reuse in mind, aided, and will continue to augment, the development of a suite of software modules that can be reused repeatedly with only minor modifications. There will always be unique portions of mission computers; however, if developed correctly using open architecture concepts, there will be a large quantity of reusable system software.

In the mission computer case, open architecture concepts tied in very closely with the use of COTS systems and components. By selecting an industry standard VME chassis, an open architecture was effectively created. Taking this a step further and requiring the use of a real-time operating system like VxWorks® made for an even more desirable environment. This environment easily supported each of the key components of open systems:

- Interoperability
- Portability
- Scalability

The investigation into mission computers and their architecture provided good insight into the benefits of COTS hardware and software, improved system and software processes, and open architecture ideas. This insight will significantly aid in new product development as well as subcontract management of current and future mission computer applications.

The efforts of the ASTI program resulted in the following list of accomplishments:

- Dual-use data acquisition system hardware and software using COTS components.
- BARS software components for design, evaluation, and real-time use in instrument display systems.
- An increased awareness of the advantages of open system architectures.

These lessons learned are already being applied to both military and commercial programs. ASTI not only provided this concrete list of accomplishments, it also provided an increased knowledge base that will improve in-house development and subcontract management now and into the future.

In short, commercial off-the-shelf parts and processes, improved system and software processes, and open architecture concepts can not only provide more elegant solutions, but solutions that are also more cost effective for military as well as commercial businesses.

Supplier Selection

Selection of vendors has long been a function of lowest cost with compromises made in technical, program management, and past performance areas. The mandate to select the "best value" supplier has forced the source selection group to scrutinize their previous process for competitive procurement, and to modify their definition and implementation of "best value". History has shown that cost has driven the procurement decision, while technical scores tended to cluster together, with small score differences even if there were large technical differences in the proposals. Recent selections have placed more emphasis upon technical and past performance scoring, and have normalized proposal scores so that technical and past performance scores have more weight in the final score, and therefore, the supplier selection. Two examples include the H–1 Upgrade Program selection of Litton for major cockpit subsystem supplier, and the V-22 Full Flight Simulator selection of FlightSafety International as the supplier of simulator elements.

AIRCRAFT-LEVEL INTEGRATION FACILITIES

Another risk reduction activity that reduces the cost of mission equipment package development and provides confidence in the overall success of an aircraft upgrade program is an aircraft-level integration capability. Subsystem development, when tested within the supplier's environment, then must be commingled with all other components of the mission equipment package to be put through the rigors of aircraft-level testing. Typically, these subsystems have been tested via interface protocols with emulated signal and sensor inputs, but have not received actual communication from aircraft avionics. Aircraft-level systems integration, which includes systematic tests which may be run in batch form, are conducted on the aircraft integration bench, and any problems found are scrutinized to identify the subsystem at fault, the root cause, and any necessary workarounds or fixes.

Over the past fifteen years, Bell has evolved a high competence level in the design and fabrication of aircraft-level systems integration benches. This evolution began with the Model 400 bench to provide cockpit subsystem developers with the capability to test their units in the context of the aircraft, and includes breakout of all aircraft signals, emulation of these signals, setting and clearing aircraft faults that annunciate Warnings, Cautions, and Advisories. Tests can be repeated and optimized via automation. This evolutionary development of aircraft-level bench test capability migrated to all other Bell programs. For example, the OH–58D, CFUTTH, Bell-Boeing V–22, H–1 Upgrade Program, and Bell-Agusta 609 programs all have utilized aircraft-level integration benches, which are still in use for those programs with ongoing upgrades, modifications, or field problems.

For past integration benches, Bell utilized a set of cards developed in-house, called Universal Electronic Test Set (UETS) cards, which contained the capability to emulate sixteen signals of discrete, analog, monopole, thermocouple, and other types of signals and sensors. One chassis could house up to sixteen cards, and a set of three chassis could be accommodated in one rack. The Bell-Boeing V–22 Electronic Systems Test Lab (VESTL) utilizes two racks—or a total of over 2,000 signals in the mission equipment package. Software to control these signals, and to communicate with the aircraft systems, was coded in C++, also in-house.

COTS technology specifically geared for testing has advanced, and so for new aircraft-level benches, Bell is instituting a new set of hardware and software constructed to test all aircraft subsystems, both in the hardware and software domain, and with the option of automating tests using new scripting features. These new components are

- VME National Instruments Mxi© interface – PCI to VME memory space converter.
- LabWindows CVI© – test software package.
- Windows NT© – operating system.

The Bell-developed integration benches are designed for portability, and can be broken down quickly for transport to any aircraft test site. The V–22 test bench has been disassembled and moved to the location of aircraft flight test in support of the Engineering Manufacturing Development program, and will be disassembled and moved again to support Low Rate Initial Production.

The fabrication of two aircraft-level integration bench facilities is currently in progress: one for the H–1 Upgrade Program, and one for the Bell–Agusta 609 program. The H–1 Integrated Test Station Floor Plan is depicted in Fig. 4, followed by a diagram of the bench architecture in Fig. 5.

The Bell–Agusta 609 Vehicle Management Systems Integration Lab (VMSIL), also in development, represents the most complex and robust integration bench ever built at Bell. It provides three separate system test capabilities: one for the avionics systems, one for the electrical systems, and one for the flight control system. These can be employed independently or simultaneously based upon test requirements. This bench also ties in the aircraft math model via a Silicon Graphics host machine, which allows complete testing of the flight control system. Test scripts have been written to provide batch test capability for rapid system testing for software and hardware releases to the VMSIL. In addition, the VMSIL has mission record and playback capability, which will make anomaly investigation easier. A block diagram of the Bell-Agusta 609 VMSIL is included as Fig. 6.

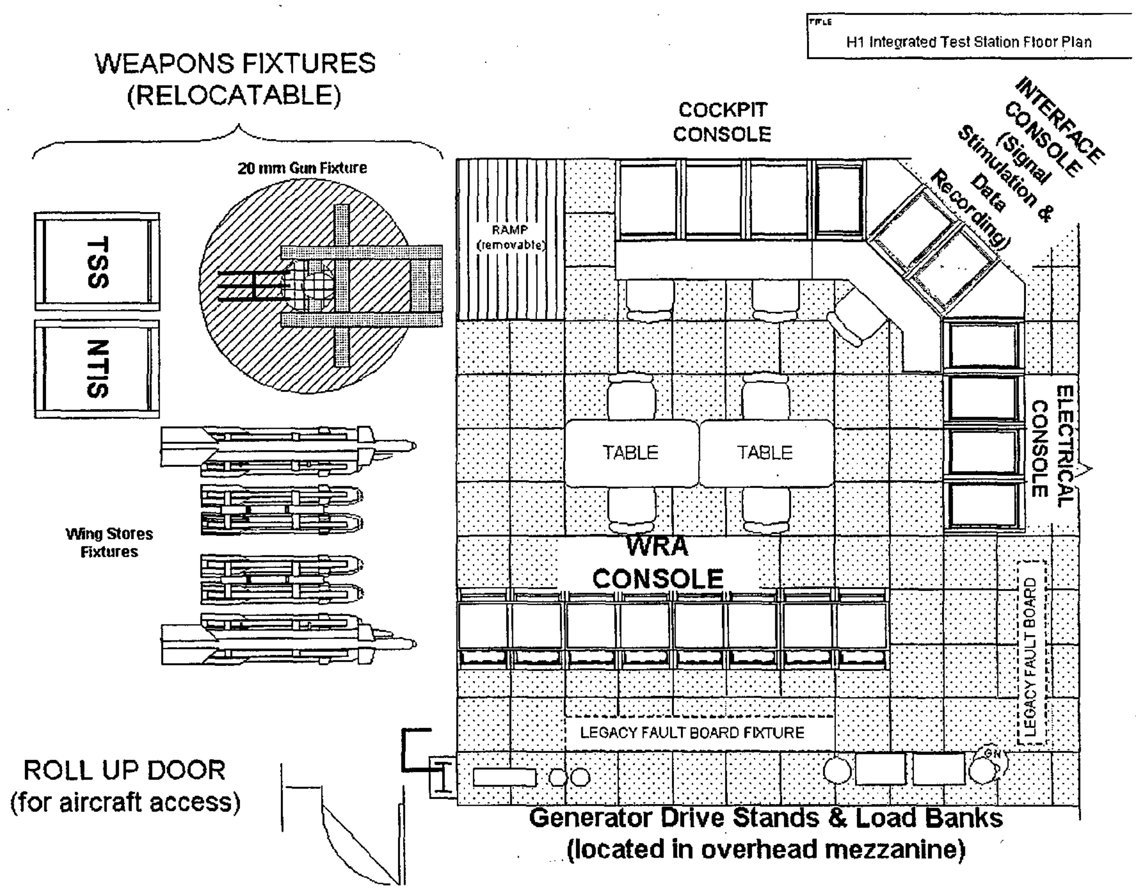

Fig. 4. H–1 integrated test station floor plan.

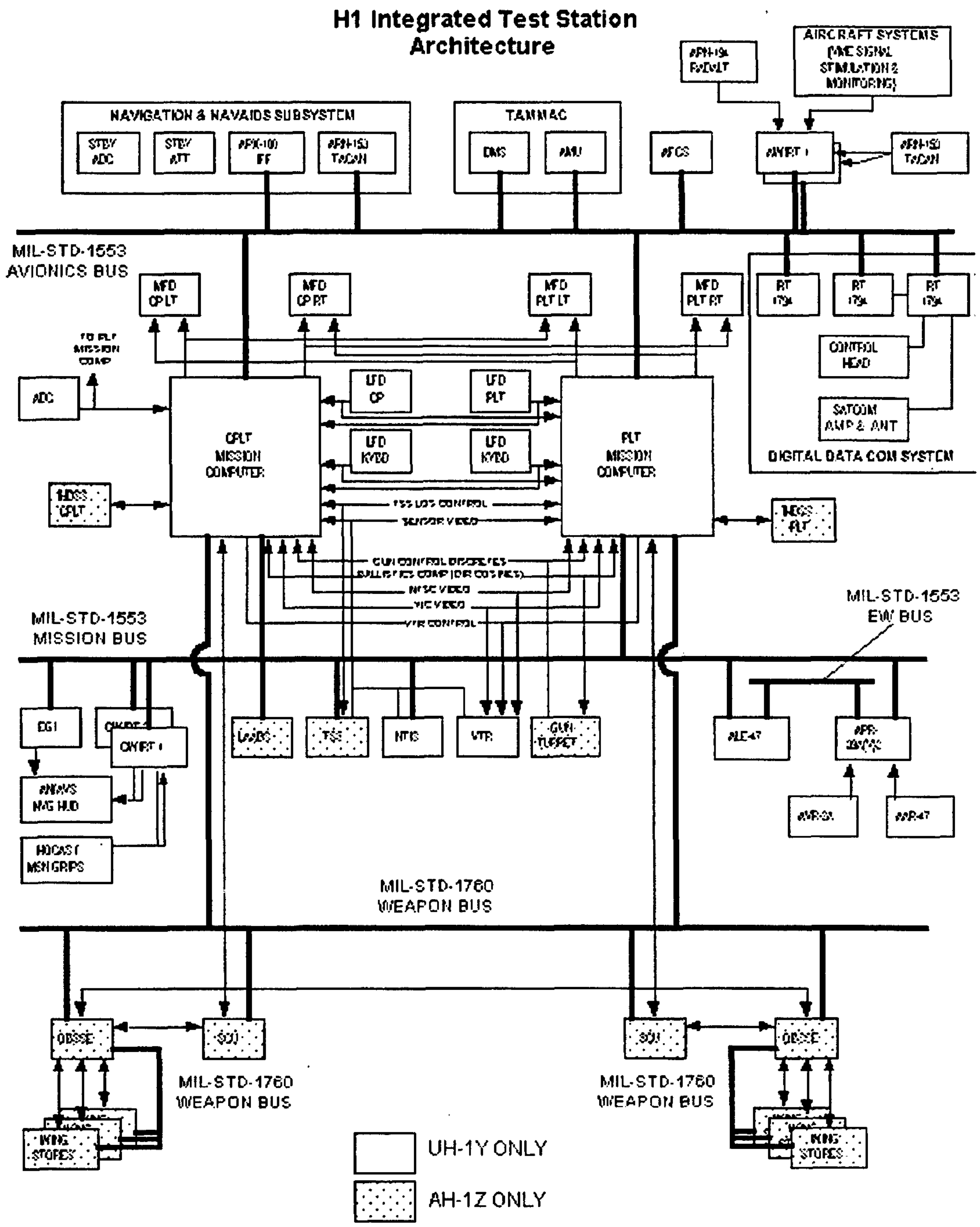

Fig. 5. H–1 integrated test station bench architecture.

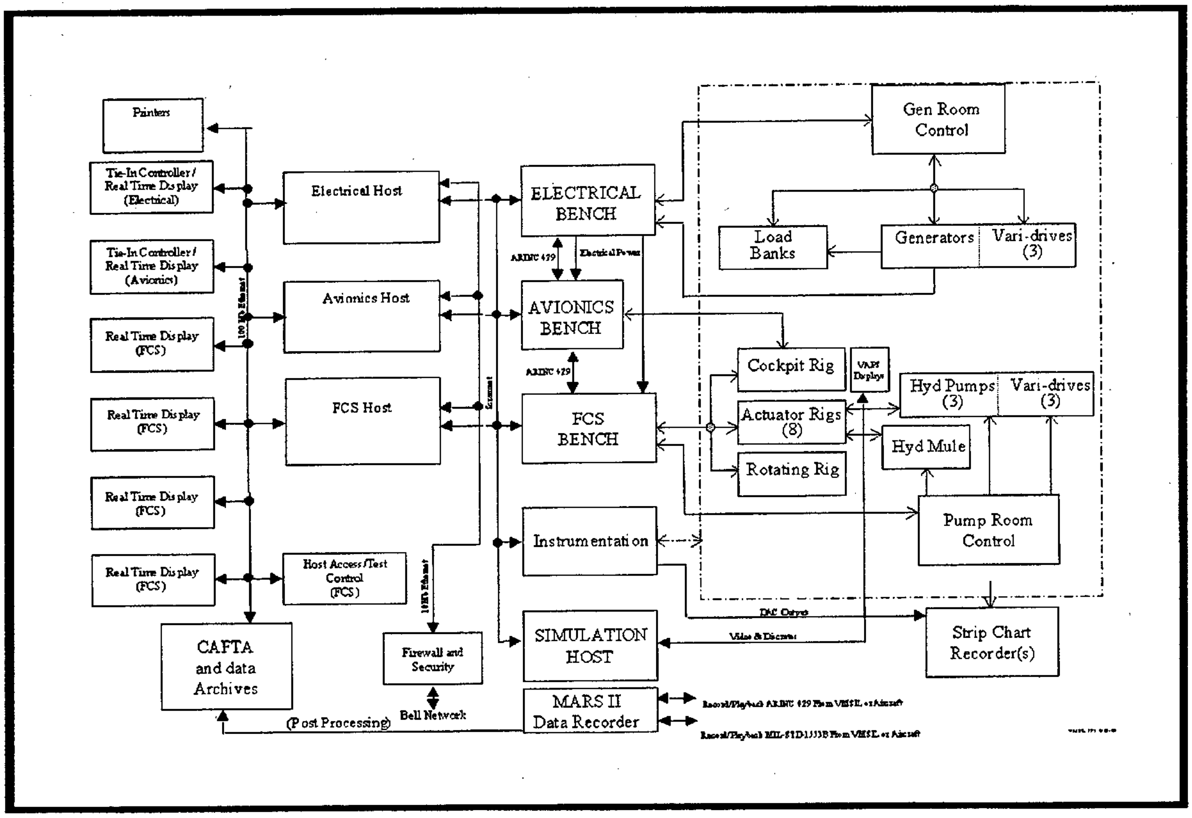

Fig. 6. Bell–Agusta VMSIL data system architecture.

TRAINING SYSTEMS

In order to minimize actual aircraft test time for crews and maintainers, it is important that economical, off-aircraft training is available and concurrent with the aircraft configuration.

Training needs can be met with simulation trainers, such as

- Engineering simulators.
- Flight simulators, with and without motion.

Engineering simulation is necessary for cockpit development, and provides interaction, familiarization, and hands-on experience for pilots, customers, and crew systems developers. Bell has an outstanding capability in the engineering simulation environment, where cockpit studies yielded optimal design and development of handling qualities, flight control laws, crew station ergonomics, and cockpit displays for the V–22 aircraft with variants, as well as for the H-1 Upgrade Program. The Bell engineering simulation is performed using

- ESIG 4530© – Visual system.
- SGI Origin 2000© – host computer.

Flight simulation is the next step for crew training, and Bell is in the forefront of state-of-the-art development on its V–22 Full Flight Simulator (FFS) program. Bell-Boeing selected FlightSafety International (FSI) as a design partner, and each partner has fulfilled design requirements for those areas in which they excel. The worksplit between Bell and FSI on the V–22 FFS was determined to maximize core capabilities both Bell and FSI: Bell is responsible for technical oversight, the aero performance model, math model shared memory, avionics subsystems (a combination of emulation and stimulation), data interchange, displays, and aural alerting, and FSI is responsible for providing the visual system, the cockpit and cab, and the test stations. The FFS is currently ahead of schedule and is underspent, and is expected to deliver up to five months earlier than its scheduled December 2000 delivery date, to New River, North Carolina, to begin 24-hour-a-day, 7-day-a-week training for the customer.

With aircraft concurrency as a requirement for the V–22 FFS, Bell-Boeing conducted trade studies in order to determine those avionics components most likely to be frequently modified, and utilized actual aircraft components for those items. For example, the mission computers for the V–22 frequently undergo software modifications to add functionality or resolve problems, and so the actual aircraft units are used on the FFS, although when the mission computer development is considered mature, the mission computer function will be emulated. Other subsystems are also emulated in the aircraft software for the FFS. When software changes are made to the aircraft mission equipment, they can be easily and rapidly rolled into the V–22 FFS configuration, thus keeping the training concurrent with the aircraft.

In addition, with commonality between devices a customer desire, Flight Training Devices (FTD) also contracted by the customer for the V–22 program will be implemented with the same hardware and software as is the V–22 FFS, with the exception of the motion base. This approach minimizes non-recurring cost, and provides the customer an FTD before its scheduled due date. Updates, spares, and maintenance issues are addressed identically for both training device types. Fig. 7 shows the V–22 FFS integration architecture block diagram.

SUMMARY

Aircraft manufacturers face tremendous challenges in today's military environment where the customer's desire for cutting edge technology frequently outstrips available funding. The challenge for Bell and other aircraft manufacturers is to meet customer expectations while maintaining the delicate balance between cost, development time, and performance.

In order to meet this challenge, it is imperative that aircraft manufacturers improve their technological expertise and their development processes. This means a corporate commitment that may require internal investment.

Discipline in systems engineering can yield outstanding results in aircraft upgrade implementation, particularly in

- Definition of the mission equipment package.
- Delineation of the mission equipment package architecture.
- Allocation of requirements to the aircraft subsystems.
- Selection of suppliers that meet subsystem requirements with strong technical solutions and past history of program success.
- Collection of "lessons learned" at aircraft upgrade program completion.
- Investment in process improvements:

1. In-house avionics development.
2. Smart buyers of avionics from outside suppliers.

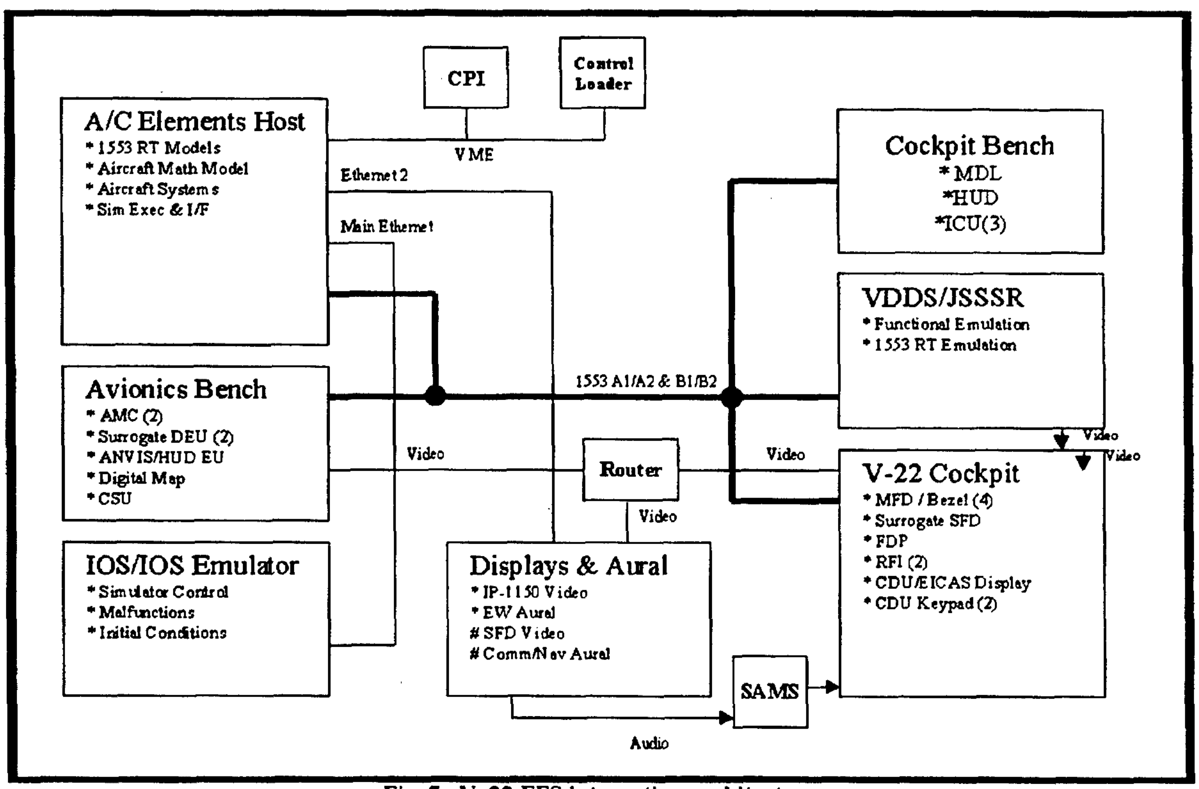

Fig. 7. V–22 FFS integration architecture.

- Investment in product development knowledge.

- "Best value" supplier selection.

Following the detailed design and development period of an aircraft upgrade program, all subsystems must be assembled at one point prior to aircraft installation. While each subsystem may be operational in their respective test environments, their interaction in an aircraft-level integration environment is required in order to reduce on-aircraft testing and to resolve anomalies that could result in safety issues on the aircraft. Robust bench testing, in a location near the air vehicle, particularly during the development period, ensures that aircraft test time is optimized to expend flight time on only those functions that cannot be tested in a laboratory environment.

Lastly, off-aircraft training in a simulated environment reduces costly aircraft time for the development of cockpit displays and ergonomics and for aircrew flight training.

Bell Helicopter Textron has made significant investments in these processes and technologies, and has added "Systems Integration" to its list of six core competencies. For Bell, and for other aircraft manufacturers, the consideration and institutionalization of these elements into the engineering process adds a powerful tool for addressing the formidable task of introducing aircraft upgrades that are affordable and provide "best value" to the military customer.

Integration of Defensive Aids

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ABSTRACT

This paper, arising from project and research work at DERA UK, considers the application of, and options and possibilities for, the integration of electronic combat (EC) equipments, specifically defensive aids systems (DAS) into air vehicles, focusing upon the problems and issues of retrofit and upgrade programmes.

The paper describes the threat to air platforms, citing both intense conflict and peace - keeping scenarios, and introduces the potential advantages of fully integrated defensive aids in terms of aircraft survivability, and in contributing towards overall situational awareness.

The retrofit and integration of defensive aids into an in-service aircraft present some challenging problems. The level of integration is a determinant of the cost and complexity of the programme. The choices range from the basic mechanical integration of separate subsystems; through the integration of a defensive aids system within itself; the integration of the system into existing cockpit displays and controls and into other avionic systems; to the ultimate level of integration in which the defensive aids become an intimate part of the flight avionics suite.

The style of avionics and cockpit controls present in the target aircraft is another key factor in the cost and complexity of the upgrade task. Retrofit into well integrated avionics, and multifunction displays, implies that software modification, and hence re-certification, will represent a major part of the integration task.

The paper describes the features of integration which may be achieved at the different integration levels. A high level of integration is needed to facilitate data fusion, an important contributor to situational awareness. The paper discusses the structure of data fusion implementations, and the accompanying problems.

Modifications and additions to ground support elements are identified as essential to the success of the retrofit or upgrade programme as a whole.

The desired level of EC integration will be driven by the customer's specification, which in turn is scoped by his understanding of the detailed issues in integration: the features and facilities which are both feasible and operationally useful. The risk exists that integration features may be sacrificed to contain costs, resulting in fits of expensive and capable items of kit which cannot be used operationally to their full potential.

1. INTRODUCTION

1.1 The Air Environment

Current military air platforms are required to operate in an environment which can contain a high level of threat. Anti-air threat systems have proliferated, diversified and generally improved in effectiveness in recent years. Anti-air systems are in the field which make use of wide segments of the electromagnetic spectrum, from radio frequencies, through infra red to the visible bands. Anti-aircraft missile guidance methods range from passive infrared seeking, through semi-active systems in which missile seekers lock to illumination of the target from the launch point or some associated system, to active radio frequency seekers. Some systems rely in whole or in part upon manual guidance from the firing post.

Threat types span the long range surface or air - launched missiles, through vehicle - mounted ground mobile missile or gun systems, to man-portable air defence missile systems (MANPADS).

Major conflicts could see the deployment of a wide range of anti-air threats. However, there is increasing emphasis within NATO on the lower intensity peace keeping or policing actions - operations other than war. In these scenarios the MANPADS and gun systems are likely to represent the major threat.

1.2 Platform Self Protection

In the face of an increasing level of threat to air platforms, nations have responded, or are likely to respond, by retrofitting or upgrading elements of defensive aids systems in their aircraft.

A **Defensive Aids System** (DAS) comprises a suite of sensors, effectors, algorithms and human-machine interfaces which seeks to enhance the survivability of a military platform or formation. A DAS seeks to combine and present information from a range of sensors to provide situational awareness, and timely warning of threats. It seeks to identify, characterise and prioritise threats in order to command the most effective use of countermeasure strategies including avoidance, tactical manoeuvre, emission control, radio frequency or electro-optic countermeasures and shoot-back systems.

Defensive aids systems are typically made up of a selection of sensing and effecting elements.

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

Additionally, defensive aids systems may make use of, or further process information from, other sensors such as radar, imaging and identification systems, from intelligence sources and from off-board sources.

A DAS may be implemented in a distributed form to protect a fleet or formation.

1.3 Defensive Aids in the Context of Electronic Combat

The term **"electronic combat" (EC)** covers the non-image-delivering military use of the electromagnetic spectrum. It includes all aspects of denying, confusing or deceiving the enemy's use of the EM spectrum, both imaging and non-imaging, and the exploitation of his use of the EM spectrum to one's own advantage. Electronic Combat covers passive sensing and geolocation of threats, defensive RF & EO sensing, alerting and countermeasure systems, RF and EO stealth, directed energy weapons and all types of jamming system.

Defensive aids sensor and effector systems can provide many of the elements of an airborne EC capability.

1.4 EC Systems and EC Systems Integration

The traditional DAS concept is focused upon detecting and countering immediate threats from missiles and guns - when the platform is under attack, the first priority is survival, and equipment designs have reflected this imperative.

The systems view of EC for platform self-protection adopts a three layered approach toward optimising platform survivability:

a) <u>Threat avoidance</u>: Traditionally this form of protection has been achieved through mission planning and intelligence. In flight, detection by the enemy is minimised by the use of terrain cover through low flying, and by control of the exposed platform signature. *Integrated* EC systems can offer long range passive sensing of pop-up threats, permitting in-flight mission re-planning.

b) <u>Minimising Danger</u>: The platform can attempt to confuse or suppress enemy surveillance and acquisition systems, or reduce the ability of the threat to successfully engage by choice of altitude, or by flying tactics. Where it is not possible to avoid a threat, nor to suppress detection, then it is feasible to select the most favourable approach geometry, to minimise exposure and to deny engagement opportunities to the enemy.

c) <u>Close in defence:</u> The defensive layer is invoked only if a threat is engaging the platform. Here the EC components providing close-in threat warning cue countermeasure effectors which attack some aspect of the incoming threat's ability to locate or damage the platform.

A common thread in all three layers is the need for situation awareness. The design of a DAS or an EC system fit to an aircraft must be biased firstly towards providing a good general observational and alerting capability relating to threats, secondly towards offering a range of countermeasures. This is because, without knowledge and situational awareness, countermeasures as separate entities are of little use.

EC systems integration, encompassing all sources of information available to the platform, offers the *potential* for long range situation awareness by forming a comprehensive picture of threat positions and identities.

2. LEVELS OF INTEGRATION

The level of integration of a new or upgraded defensive aids system, is a determinant of the cost and complexity of a retrofit programme. The choices range from: (i) the basic mechanical integration of separate subsystems, each complete with its own set of displays and controls; through (ii) the integration of a defensive aids system within itself, including some common means of display and control; (iii) the integration of the system into existing cockpit displays and controls alongside integration with other avionic systems such as communications, weapons and weapon aiming and to terrain databases; to (iv) the ultimate level of integration in which the defensive aids become an intimate part of the flight avionics suite, whether in a federated or integrated modular avionic architecture.

2.1 Basic Mechanical and Electrical Integration

The basic mechanical integration of new units or sub-units, represents the simplest and cheapest approach to DAS retrofit. Some self-contained sensor or effector unit is procured from a subcontractor. The task of the systems integrator is then one of mechanical integration of the main unit or units, its sensor or effector heads (which will usually require mounting on or through the airframe, that is, *apertures* must be provided), its crew controls and displays and of cabling between sub-units.

The integrator must arrange for the provision of power and typically a few electrical or electronic signals containing for example navigational data and platform velocity. The total effect of the retrofit must be assessed in terms of the total platform weight, aerodynamic drag due to external fitting, and changes to centre of gravity and moments of inertia.

The greatest challenges lie firstly in the area of crew controls and displays. Units need to be positioned within sight and reach of the crew, and suitable cockpit space is typically hard to find.

The second critical area is in the positioning of sensing or effecting apertures. External space is often very limited, particularly on small airframes, and all prime locations will often be occupied by existing systems. DAS sensors and effectors demand clear fields of regard or specific directions of fire, with numerous individual constraints.

Optimal placement of sensors and effectors requires extensive study work covering not only the performance of the system in question, but also its effects on other systems, on flight safety, and whole platform performance.

Significant costs are incurred in the area of flight safety testing and re-certification following such a retrofit programme.

This style of DAS integration may deliver a total system in which the individual subsystems are poorly linked and integrated, both with one another and with other relevant aircraft systems. Some limited integration features, for example permitting a sensor to directly trigger a countermeasure, might be realised. In the main, however, sensor data is merely made available in some way to the aircrew who then have to perform cognitive and decision processes, and initiate correct and timely countermeasure responses. Furthermore, these data are typically not presented in a centralised and optimised form, but distributed among a number of display units.

The situation described could evolve from the procurement and installation of add-on systems on the basis of operational need; but this to a degree is inevitable when global operational scenarios rapidly change and new and unexpected threats arise and demand urgent solutions. Of course, this situation does not apply to DAS alone, but to a cross section of avionic systems and functions. The result, apart from the difficulties that aircrews could have in operating such platforms effectively, could be a proliferation of build standards. If a fleet of aircraft is to remain in service for a significant length of time, then the ever increasing cost of maintenance would eventually dictate some sort of rationalisation programme to harmonise build standards across the fleet.

2.2 Integrated Defensive Aids System

An **Integrated Defensive Aids System** (IDAS) typically comprises a suite of sensors and countermeasures designed to offer its host platform a range of self protection options, against a variety of threat types.

An IDAS is integrated within itself, and will typically be procured through a single subcontractor. There will be some central integration function, a DAS control element, which might be realised in a discrete unit or sub-unit, or embedded in some other part of the system. Sub-units will be linked by some sort of communications bus. The system will be provided with a common display and control unit or function.

The DAS control element should act as an automatic integration engine, servicing common DAS displays and controls, and assisting the pilot's decision making by suggesting, or even implementing, countermeasures.

It should provide data formatting and conversions, association of threats declared by various sensors, kinematic data fusion, resolution of any conflicting threat identifications, overall threat prioritisation, and the trigger for appropriate countermeasure deployment. It should also provide a common channel for DAS data logging, common DAS status and error reporting, and a common point for loading DAS mission software.

Additionally, the DAS control element should provide the link between the DAS and the aircraft avionics. It should accept and distribute basic data from the aircraft navigation system such as aircraft position, velocity and heading, and data such as time reference and status.

The main benefit of an IDAS is that a central control unit can hold a library or database of integrated countermeasure responses to threats. In un-integrated DAS implementations each warner - countermeasure group would hold its own such library. In an integrated solution there is scope for better identification of threats, better tracking of threats and hence improved application of countermeasures.

The integrated system should be able to estimate the lethality of threats and prioritise them for DAS countermeasure response, then select the most appropriate countermeasure tactic against a detected threat (where such tactics could include a recommendation for manoeuvre). It should be able to allow for uncertainties in identification and deploy counters to a number of likely threats simultaneously. It should also be able to counter mixed mode threats, as well as truly multispectral threats. It must arbitrate the needs of DAS sub-units; effective sensing, for example, may require that effectors be silenced or inhibited periodically to allow for look-through, with minimum disruption to the countermeasure effect. Lastly, it must be able to decide or recommend when to cease countering a threat.

An IDAS should, by virtue of its architecture, offer the growth potential to cope with a wider range of sensor and countermeasure types.

The task of the platform systems integrator is similar to that in 2.1 above. There will be considerations of the supply of power and signals, of platform weight, centre of gravity, and aerodynamics, of placement of sensors and effectors, and of crew controls and displays. The costs of flight safety testing and re-certification following an IDAS retrofit programme will be significant, but probably less overall than if the sub-units of the IDAS had been retrofitted in separate programmes.

The placing of an IDAS crew control and display unit may be more or less difficult than the task in 2.1 above: only one unit must be accommodated, but it is likely to be larger and more complex than any of the several separate units it replaces.

2.3 IDAS with Avionics Integration

This third level of integration represents a major step towards full integration between the individual elements of which the DAS is comprised, and between the DAS as an overall entity and the aircraft avionics system.

The main advances over the IDAS concept of section 2.2 are:

a) Integration with cockpit multifunction displays;

b) Integration with avionic systems, sensors and databases.

2.3.1 Display Integration

Multifunction display and control units are present in the current generation of civil and military aircraft. They offer large TV-style displays which can be programmed to represent a variety of instrument types, as well as maps or map-style displays for piloting, navigation and targeting. They are typically menu structured allowing the aircrew to navigate through a wide range of display content and formats. They offer programmable key functions, through touch-screen technologies, for crew interaction. Audio tone and voice warnings, and even voice entry of data and commands, are sometimes offered in addition.

Such displays are driven by powerful computing elements which *in principle* offer a simple means of integrating new data type and display formats. It is important at this level of integration, that crew interaction with the integrated DAS be realised through the aircraft multifunction HMI and its associated processing capability.

A major adaptation will be in the area of display formats. DAS formats should both add to and modify display pages used for piloting, navigation, communications, mission planning and weapon control. Typical formats would include:

a) Spoke - style displays indicating the bearing and priority of each threat, and the status of countermeasure deployment. All IDAS sensors producing threat bearing and/or range indications, should share this one display through an underlying data fusion process;

b) Tabular text and/or graphic displays for the monitoring or set-up of operational parameters, or parameters required for trials, evaluation or acceptance testing as required by the elements of the IDAS;

c) Map type displays with threats shown at their estimated positions. If digital or digitised maps are available then these should form the underlay for map - style displays. Tracks which have converged in range, can be shown at their estimated positions relative to the map. Bearing-only tracks, representing high priority threats, may be displayed as spokes relative to own ship position on the map.

A useful addition on this type of display is the overlay of threat lethal zones and/or threat detection zones. It is important that DAS information be available for display on the map - style display pages which are used for piloting, navigation, route planning etc., and those used for display of the air picture as received via a communications medium. In this way the current threat situation can be used by the crew to plan avoidance and adjust flight plans;

d) There should be means for an IDAS recommendation for tactical manoeuvre to be displayed.

The adaptations described above represent the ideal. However, the re-programming of multifunction displays can be an expensive exercise. The risk exists that when cost trade-offs are made, the retrofit implementation may support only a few additional DAS - specific display pages, with little or no integration of DAS - derived information with that from other sensors, communications, or mission data.

The second cost-related risk is the omission of adequate display of DAS - derived information on screens used for piloting and flight planning. The positions of threats known at the time of mission planning may be seen by the IDAS sensor suite to have changed; the omission of such important data from flight planning screens would represent a serious gulf between capability and realisation.

2.3.2 Avionics Integration

An IDAS can potentially make use of threat and supporting data coming from any of the following avionic functions:

a) on board targeting sensors such as radar and infrared search and track;

b) pilot visual designation;

c) pre-mission database information on the locations of known threats;

d) geographic or terrain databases offering, for example, intervisibility plots;

e) off board threat data arriving via some communications system.

The IDAS should be capable of responding to commands from the mission avionics (but which may originate from the pilot), for example:

a) to ignore a particular threat;

b) to invoke a particular style of countermeasure;

c) to silence emitters.

The effective use of avionic data, and the means of acting upon commands, presents a challenge to the IDAS subcontractor particularly in the area of system test and acceptance. The more deeply embedded the IDAS becomes, in the mission avionic system, the harder its becomes to prove its functionality as a separate entity.

The avionics or mission system can potentially make use of DAS - sensed data, and offer capabilities such as:

a) forming a (data fused) air and surface picture from all available sources including IDAS - sensed data;
b) aligning optical or thermal sights to an IDAS - detected threat or target;
c) aligning a search or tracking radar to an IDAS - detected threat or target;
d) aiming a designator or weapon against an IDAS - detected threat or target;
e) acting upon an IDAS recommendation to silence some or all emitters;
f) communicating IDAS data off board.

IDAS data collected in flight should be logged, and this data log integrated with any other mission level data logging facility.

IDAS training features should be integrated with any more general on-board training suite.

The mission system should perform the high level control and tasking of the IDAS. It must direct decisions on how to deal with some particular threat. This could involve mission replanning, weapons assignment, tactical advice, emission control, or an IDAS response. The final arbiter should in most cases be the pilot - the system, however, must be able to offer the most effective options, and act upon his or her command.

The platform systems integrator must provide data to the IDAS in a timely fashion, and provide the enhanced functions and capabilities.

It may be simplest to give the IDAS access to a suitable avionic systems bus, if such exists. However, it is inevitable that considerable changes must be made to existing avionic systems software, and that some changes will impact upon flight-safety-critical functions, implying considerable costs in re-certification of the software suite as a whole.

2.3.3 Suitability for Retrofit or Upgrade

It is difficult to implement the features of integration described above, as part of a DAS retrofit or upgrade programme. The level of difficulty, and hence expense, increases as the number and depth of integration features increase.

Practically, such a level of upgrade is best tackled as part of a larger aircraft upgrade or refit programme. In this way the considerable cost of flight safety testing and re-certification may be spread across a number of system improvements.

2.4 DAS Integrated within a Federated or Modular Avionic System

This represents the ultimate potential level of integration of DAS and avionics, in which the DAS is no longer identifiable as a separate entity. DAS sensors should operate alongside other sensors such as radars and infrared search and track, as an integrated sensor suite offering the aircraft a wide coverage of the electromagnetic spectrum, with both active and passive capability. DAS effectors should operate alongside other effectors, such as weapon systems, offering a variety of means for both conducting and surviving a mission. A central controlling and scheduling function should interact with the sensors, effectors and crew, as well as with other avionic systems such as communications and navigation, and mission databases, to command responses to the sensed environment.

2.4.1 Federated System

A federated avionic system is one in which subsystems, central computing elements, and display and control units are linked together by some sort of communications bus, permitting exchange of both data and commands. One unit will act as a master controller regulating bus activity. The units connected to the bus will often be of widely varying types, procured from many different sources, and performing unique functions. Mil Standard 1553 has been a common choice of bus standard, although the bandwidth it offers is limited. In many realisations of federated architectures, several separate busses connect major subsystems together, with a few special units providing gateways between these separate busses.

2.4.2 Integrated Modular Avionics (IMA)

An IMA system is one in which all, or at least a major part, of the signal and data processing functions in the aircraft are implemented in a core system comprising a set of standard data processing and signal processing modules.

The main advantages of this approach arise from the commonality and replaceability of modules, reducing spares holding and maintenance requirements. An IMA should allow for additional or upgraded modules to be inserted into the system with no other hardware or software modification. If reconfigurability is built in to the IMA architecture, then the aircraft can be equipped with "spare" hardware capacity, allowing for module failure to be circumvented and thus improving the availability of the aircraft as a whole.

There are several possible styles of IMA, and IMA concepts vary in scope. A core IMA might consist only of data processing or general computing elements.

A more ambitious IMA implementation might include high speed signal processing elements, and the most advanced concepts would also include high speed digitisers, and programmable ASIC hardware to take direct input from sensors of many types.

2.4.3 Level of Integration

Federated and IMA architectures are often marketed as offering an inherently high level of integration, however, this is not the case. Integration always costs time, effort and money; these architectures certainly *facilitate* advanced integration, but the cheapest solution may offer minimal functionality. The traditional division of industry into subsystem specialists has tended to offer the system integrator with a series of independent subsystem packages, even when these are implemented within a highly integrated architecture. If an integrated system solution is to emerge, then the systems integrator needs deep involvement in every subsystem, from the stage of initial specification, onwards.

The *goals* of EC integration are the same as those listed in 2.3.1 and 2.3.2, however, the means of achieving these goals can be better managed:

a) Centralisation of the plan formation, scheduling and decision making functions of all the avionic subsystems, avoiding conflicting and overlapping decisions which could arise from subsystems controlled locally. This centralisation also offers better control of the pilot's workload, and communications channel capacity.

b) Multi-functionality of sensor and effector assets can be implemented more readily. The problem of time scheduling the use of shared assets can be tackled centrally.

2.4.4 Retrofit Issues

Advanced federated, and IMA avionic implementations are too new for practical problems of retrofit to have emerged, however, some of the likely key issues may be anticipated:

a) Even the smallest change to a federated system's bus traffic, or an IMA system's application code, will involve costly system-level test and verification. The systems integrator must maintain a comprehensive emulation test bed, with facilities for monitoring bus, processor and memory loads, latencies and areas of real time criticality.

b) In the context of multi-functional sensor and effector assets, any upgrade to a single functional area must be assessed for its impact on all other functions which that sensor or effector has to perform.

3. INSTALLED PERFORMANCE

The mechanical integration of retrofitted DAS elements, in particular of sensor and effector apertures, can be costly and may limit the performance of systems.

Effector aperture placement, can suffer from the problems of airframe obscuration.

The placement of radio frequency receiver apertures in particular, also of electro-optic apertures, can pose considerable problems due to the disruption of signals arising from airframe shadowing and reflections.

These difficulties imply a need for thorough and comprehensive flight trialing of installed performance parameters.

The issue of installed performance also has the potential to cause contractual difficulties, with a blurring of the responsibility for achieving contracted performance parameters, between the DAS subsystem contractor and the airframe prime.

4. LOGICAL INTEGRATION

All subsystems which react to information require to be fed with concise and reliable inputs. The aircrew is arguably the most important user of, and reactor to, information. A vital function of an integrated DAS should be to remove confusion and information overload from the pilot.

Sensor and other data sources must be combined, compressed and presented. This aspect of integration, tackling the logical integration of the data offerings of retrofitted kit, should be given consideration in any upgrade programme. The risk exists, that as a result of cost trade-offs, data fusion may be dismissed as too difficult, too costly and of insufficient importance, or at best tackled superficially.

4.1 Data Fusion

Data fusion offers a family of tools and approaches to the systems integration problem outlined above.

The complex field of data fusion is typically divided into a number of levels, representing stages in the chain of processing of data.. Table 1 below describes the levels of the JDL-97 five-layer model of data fusion processes (pre-processing, object refinement, situation refinement, impact assessment and process refinement), and the similar OODR model (Observe, Orient, Decide, React), which map well onto the problems of integrating DAS sensors and effectors both within themselves and with other aircraft sensors and information sources:

Fusion at level 1 is firstly concerned with the optimal estimation of target kinematics. Typically this involves combination of measured data from more than one sensor source.

An IDAS will typically include one powerful long range sensor, a radar warner or ESM, able to locate and identify threats. There is a key role for data fusion at level 1 even if a radar warner/ESM is the only sensor considered - *temporal* fusion, to evolve high accuracy tracks in range and bearing from the low accuracy, bearing-only raw data (some researchers would call this tracking rather than data fusion).

The process at each time step commences with an association stage in which the current set of bearing measurements are allocated to the set of currently tracked entities (or to initiate a new tracked entity), and continues with a Kalman filter or similar algorithm for state estimation in the presence of noise. If multisensor data are available from the IDAS, the processes are identical. The fusion process will be able to converge its estimate of target range, provided there are changes in the line of sight.

In order to simplify this integration task, a radar warner should perform fusion (association) of detected emitter modes into reports of *weapon systems* before offering such reports to the IDAS / Avionics data fusion service.

Range convergence would be assisted by supporting information e.g. from off-platform data (triangulation), or from mission data regarding known threat locations, if integration of such data sources can be achieved.

Recent experiments at DERA UK, using a Kalman-filter based fusion engine, have demonstrated range convergence from simulated radar warner/ESM data [1].

Fusion at level 1 secondly tackles the fusion of identity declarations. This is in many ways more complex than the fusion of kinematic data. There exist a variety of rule-based and probabilistic approaches. STANAG 4162 offers a standardised approach based upon Baysian evidential reasoning. The implementation is difficult, however, identity fusion to STANAG 4162 has been demonstrated by DERA and others, and is being implemented within NATO.

Many platforms carry a range of other sensors, such as radar, infra-red search-and-track, and visual and IR targeting sensors. Such sensors also deliver track and identity data, which should be fused as above, preferably within a single central data fusion service handling all sensing sources.

Once information from all sources on board have been fused to form tracked entity data, tracks from off-board sources and mission data on known threat locations can be fused in, provided that the integration exercise has made such data available.

Fusion at levels 2 and 3 must form threat groupings and priorities. Algorithms at these levels are typically rule or knowledge based.

The end product of data fusion at levels 1 to 3 is a machine held situation awareness, which in a well integrated system, should exist to drive a resource manager, responsible for plan formation and scheduling of various level 4 response packages. Such packages might include:

a) Selection and filtering of information for display to the pilot, to provide (cognitive) situational awareness, and to present decision options, whilst managing his or her workload;
b) Mission re-planning, re-routing to avoid threats whilst fulfilling the mission requirements;
c) Recommendations for tactical manoeuvre;
d) Allocation, timing, and control of IDAS countermeasures;
e) Targeting, allocation, firing and control of any weapon systems which might be carried;
f) Moding and tasking of IDAS and other sensor assets;
g) Reporting back of the situation to higher levels of command, and to other interested allied assets.

4.2 Data Fusion Implementation

There are three principal difficulties in data fusion implementation:

a) data fusion incest, avoided by appropriate architectures;
b) the lack of performance metrics leading to difficulties in validation and acceptance;
c) contractual barriers to satisfactory implementation.

Incestuous fusion of data is the phenomenon in which misleading or low confidence data re-enforces incorrect conclusions, and may be thought of as a form of positive feedback. False alarms may be built into tracked entities, or genuine entities lost. It can occur in networks of fusion processes, within a single platform or across multiple platforms, when true sensor data is not segregated from fused data. When the origin of the data is lost, mis-associations, tracks based upon false alarms, and measurement biases can then be passed around the network reinforcing themselves.

Data fusion incest can be avoided by strict separation of data within fusion processes. Within a single platform, a fusion engine or number of engines should associate and fuse data from the platform's own sensors to form a local track file of entities described in terms of position, heading, velocity and identity. This local track file can then be associated and fused with externally reported tracks and with tracks derived from the mission database, to form a global track file.

Off-platform track information received through some communications medium falls into one of two categories:

a) That originating from command<u>ed</u> units, for example from the fighters within a squadron. Such reports will comprise local track or spoke data. Each platform may only report its local track file, and in it turn it may accept local track file reports from nearby co-operating platforms;

b) That originating from commanding units, comprising an overall air picture, in some form. If the commanding unit has based its track upon reports received from a commanded unit, then that platform, when receiving the track, must be informed that it was one of the contributors.

Figure 1 illustrates the concept, in which incestuous fusion may be avoided.

Data fusion development has been characterised by a lack of satisfactory metrics for quantification of the performance of any product. The pragmatic approach to the testing and validation of data fusion engines has been to assess performance against test data sets in which the "true" picture is known. Research work is underway to develop scientifically based metrics against which products could be validated and accepted.

Some of the greatest potential difficulties and cost drivers in the implementation of data fusion, may arise from commercial barriers between equipment subcontractors and the aircraft avionics prime contractor. It is important in a retrofit or upgrade programme, to establish the commercial links and agreements which mirror the technical interlinkages required to realise the desired level of integration.

5. GROUND SUPPORT SYSTEMS

Any equipment retrofit or upgrade programme must address the issues of spares and servicing: Integrated Logistics Support. However, as these are not unique to DAS and EC, they will not be pursued in this paper. This section will address two aspects of ground support concerning the preparation of the mission - specific data needed for the effective use of EC in the air.

5.1 Pre-Flight Message (PFM) Generation

An essential component of an EC retrofit programme is the provision of a comprehensive facility for producing all forms of pre-flight message required by the integrated DAS. Any growth or upgrades to an in service DAS must be matched by upgrades to any existing pre-flight message generator.

Any additional hardware involved in the transfer of PFMs from the ground facility to the aircraft must also be provided.

The content of the PFM for an IDAS will go beyond the traditional libraries of threat data loaded into the component subunits of the IDAS. It must be able to assign countermeasure responses to threats, including mixed mode and multiple responses. Further PFM information will be required if the DAS is to make use of threat information coming from non-DAS sensors on board, or from any mission library of known threats and their locations.

The PFM will be required to assist in the data fusion process, in particular with the threat prioritisation stage, and with the setting of rules in any rule-based approach to the control and scheduling of IDAS responses.

Post - mission replay and analysis of logged IDAS data could be built into a PFM generation toolset, as could the generation of training scenarios.

The discussion above strongly favours an IDAS architecture requiring a single PFM, over an architecture requiring each element to be supplied with a separate PFM. Similarly a single unified toolset for generating such a PFM is highly desirable. The user will also require test equipment, such as a synthetic environment or reference set of DAS units, in order to test and verify any PFM produced.

Integration of the both the PFM and toolset generating the PFM, with the aircraft mission data and the tools that prepare it (see 5.2 below), is also desirable.

5.2 Mission Planning

An air mission is a sequence of tasks and activities needed of an aircraft, to fulfil some specific objective. Mission planning is the process of generating an acceptable sequence of tasks, given a set of constraints. The constraints typically involve the fuel and weapons load carrying capability of the aircraft, aircraft performance, the availability and disposition of air refuelling assets, civilian air traffic control, de-confliction with both civil and military air traffic, the types of terrain to be overflown and the allegiance of such terrain (i.e. friendly, neutral or hostile), the type and intensity of conflict, the level and types of threat expected, and (of great importance) the political situation and the rules of engagement.

The effectiveness of the EC suite in flight could benefit from mission planning in 4 ways:

a) Access to map referenced locations of known threats, to correlate with sensed data. Also the knowledge of friendly, neutral and hostile areas, and of civil airlanes, could assist in the identification of sensed entities.

b) The type of terrain and of likely civil emissions in any detected band, could influence false alarm rejection algorithms in EC sensors.

c) The more advanced IDAS implementations will offer a choice of self protection strategies. The "best" option might depend upon the phase of the mission, also the type of conflict and the area being overflown. Knowledge of the phase of mission could also be used to select the rules governing the display of information to the pilot, and rules determining how much of the expendables load should be used when. The pilot should remain as the final decision maker; such rules should only influence what is presented as the preferred option.

d) The moding and tasking of EC assets, particularly if shared with other avionic functions. The mission plan should generate at least a baseline rule set, allowing for variation in flight.

The generation of the mission plan should build in any new or upgraded EC capabilities. The ability to challenge some types of threat, and the remaining vulnerability to others should influence the choice of route and flight altitude.

The retrofit / integration programme should also consider:

a) The integration and standardisation of mission planning hardware and software aids (for example to bring pre-flight message generation within the scope of mission planning).
b) The standardisation of formats for data to be downloaded.
c) The integration and standardisation of the hardware involved in transferring any electronic mission plan to the aircraft.
d) The integration of software and mission data load points on the aircraft.

Mission planning will have to (attempt to) manage the pilot's workload and his or her ability to absorb information and take decisions. The more capabilities that EC (and all other) systems offer, the more important this becomes.

6. CONCLUSIONS

The perception of the threat to air platforms, both in intense conflict and in peace - keeping scenarios, has increased in recent years. This perception has prompted, and is likely to continue to prompt, retrofit and upgrade programmes, in the UK and elsewhere, involving defensive aids and other electronic combat equipments.

A key cost driver in such retrofit and upgrade programmes, is the positioning of apertures, and the consequent issue of predicting and verifying the installed performance of the kit.

Another major cost driver is the level of integration of the defensive aids system (DAS) with the platform and its avionics, and the integration features implemented.

Levels of integration range from: (i) the basic mechanical fitting of separate subsystems, each complete with its own set of displays and controls; through (ii) the integration of a defensive aids system within itself, including some common means of display and control; (iii) the integration of the system into existing cockpit displays and controls alongside integration with other avionic systems such as communications, weapons and weapon aiming, and to terrain databases; to (iv) the ultimate level of integration in which the defensive aids become an intimate part of the flight avionics suite.

The features of integration, which can drive programme costs, include:

(i) The fusion of threat and target information from all sensor sources (DAS and other);
(ii) Integrated presentation of information on display devices;
(iii) The use of DAS - sensed data to align sights, sensors or weapons;
(iv) Integration of DAS sensed data and DAS effector status with the communications infrastructure, plus the ability to make use of off-board data;
(v) The integration of DAS with mission level control and decision making functions; and
(vi) The integrated control of multi-functional or shared aperture devices.

Other on-board integration issues involve the logging of DAS and other mission data, and the integration of on-board training facilities.

The total retrofit or upgrade programme must also address ground support issues such as the generation of pre-flight messages, and the means of mission planning.

The level of integration, and the integration features implemented, impact not only upon the cost and complexity of the equipment retrofit, and the cost and complexity of new and upgraded ground support facilities, but also upon the cost of re-certification of the entire aircraft as modified.

The desired level of EC integration, emerging from a retrofit or upgrade programme, will be driven by the customer's specification, which in turn is scoped by his understanding of the detailed issues in integration: the features and facilities which are both feasible and operationally useful. It is necessary to maintain a research infrastructure, and scientific expertise, to support the military customer in this understanding.

A risk exists that, in programme implementation, integration features may be sacrificed to contain costs, resulting in fits of expensive and capable items of kit which cannot be used operationally to their full potential.

7. ACKNOWLEDGEMENTS

The work reported in this paper was carried out for Operational Requirements (Air) Directorate of the UK Ministry of Defence, under the Applied Research Programme.

This work has also drawn upon a number of project support activities funded by the Procurement Executive of the UK Ministry of Defence.

8. STATEMENT OF RESPONSIBILITY

Any views expressed in this paper are those of the author and do not necessarily represent those of the UK DERA, nor of H.M. Government of the United Kingdom.

GLOSSARY

ASIC	Application Specific Integrated Circuit
DAS	Defensive Aids System
DERA	Defence Evaluation and Research Agency
EC	Electronic Combat
EM	Electro-Magnetic
EO	Electro Optic
ESM	Electronic Surveillance (or Support) Measures
HMI	Human Machine Interface
IDAS	Integrated Defensive Aids System
IMA	Integrated Modular Avionics
IR	Infra Red
JDL	Joint Directors of Laboratorics
LWR	Laser Warning Receiver
MANPADS	Man Portable Air Defence Systems
OODR	Observe, Orient, Decide, React
PFM	Pre-Flight Message
RF	Radio Frequency
TV	Television

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JDL-97 Level	Function	OODR level
Level 0	Pre-processing, formatting, alignment of co-ordinate frames, pixel-level processing	-
Level 1 (Object refinement)	Association (of plots or tracks) with each other and with currently recognised tracks, or to commence a new track	Observe
	Fusion of plots or tracks to form entities tracked in position and heading. Optimal use of new measurement data to update track parameters.	
	Prediction (project tracks into the future)	
	Classify entities, de-clutter	
	Identify entities (fusion of separate declarations of identity, build up of identity evidence)	
Level 2 (Situation assessment	Formation of the air / surface picture (entities fused into groups, with assessment of intention)	Orient
Level 3 (Impact assessment)	Threat prioritisation	
Level 4 (Process refinement)	Plan formulation, scheduling	Decide
	Reaction packages (command DAS effectors, mode and task sensors, display to pilot, communicate off-board, mission re-planning, weapon allocation etc.)	React

Table 1 Data Fusion Functions against the JDL and OODR Models

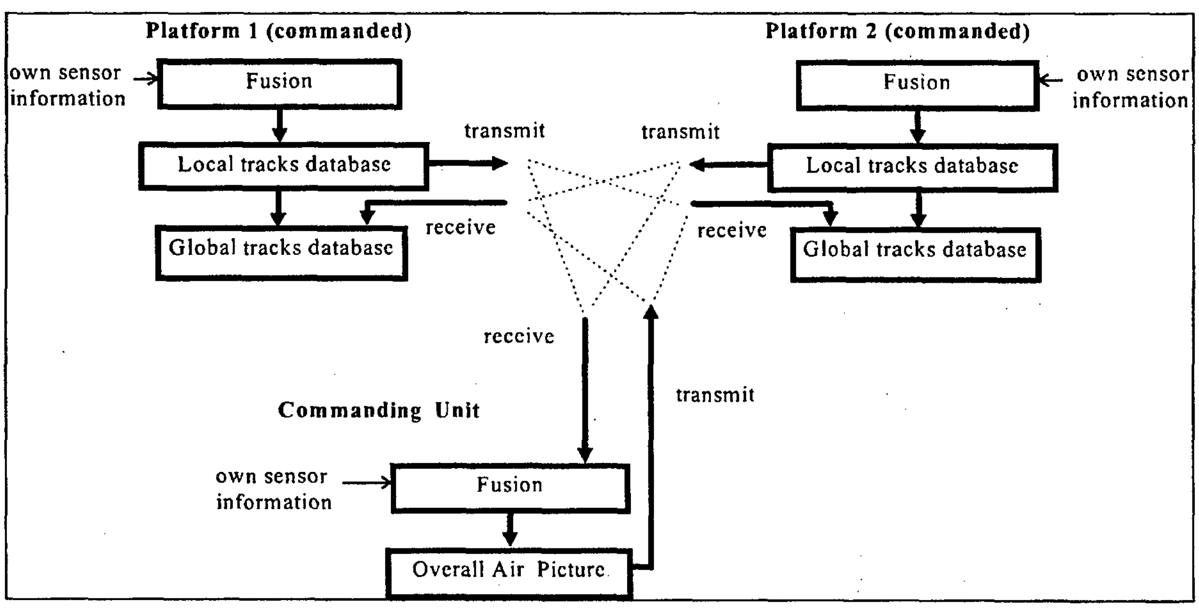

Figure 1 Data Fusion Structure Avoiding Incestuous Fusion

MODULAR AVIONICS UPGRADE : THE COST EFFECTIVE SOLUTION TO ADAPT EXISTING FIGHTERS TO THE OPERATIONAL REQUIREMENTS OF TODAY'S BATTLEFIELD

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ABSTRACT

This paper presents already fielded implementations of an avionics upgrade package developed to offer a modular solution to a wide range of modern operational requirements. The *SAGEM SA* upgrade concept allows to match specifications ranging from basics performance enhancement, such as high accuracy navigation for low level flight, up to full muti-role capability with sophisticated air-to-surface weapon delivery and multi-target air-to-air fire control.

The upgraded system implements all state of art features available on the most recent fighters, particularly for pilot interface (HOTAS, glass cockpit, NVG compatibility, ...) as well as for system architecture (modular avionics, high level of redundancy and back-up modes, ADA HOL programming, object oriented software ...).

The presentation will describe how the most recent technologies can be inducted in older platforms more rapidly than on newly developed airframes, therefore ensuring that the most demanded operational requirements are fully satisfied. In particular, sensor technologies (pulse-Doppler Radar, thermal imaging and IRST ...) will be addressed, as well as smart weapons (guidance kits, advanced fire control software ...) which are driving factors for the overall accuracy for the success of the mission.

A special highlight will be given on ground support equipment and procedures both at operational and maintenance levels. These facilities include part-task trainers and mission planning systems to help the pilots optimize their missions ; in parallel an integrated logistic support is deployed to give all necessary tools to the maintenance crews.

INTRODUCTION

With close to twenty years of experience in fighter upgrade, in collaboration with the Air forces of various countries, SAGEM has been developing and validating an integrated modular avionics concept meeting a wide range of operational requirements of the armed forces and which can be easily installed in different older or recent operating platforms.

It took place naturally through an industrial approach in order to meet the operational performance requirements while minimizing the access cost to technology required to secure the performance. As a result of this approach, SAGEM defined a **system core: the Multifunction Navigation and Attack System (MNAS)** capable of gathering all the management and control functions of today's avionics, such as:

- system mode management (Navigation, Training, A/G Attack, A/A Interception, ...)
- armament units and EW equipment management
- optimal management of Pilot/NAS interface
- radar mode automatic management
- computation of fire control parameters (visual and hearing)
- computation of accurate navigation, guidance and flight control parameters, including sensor hybridisations (GPS, Radar, Laser Rangefinder, FLIR, etc.)

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

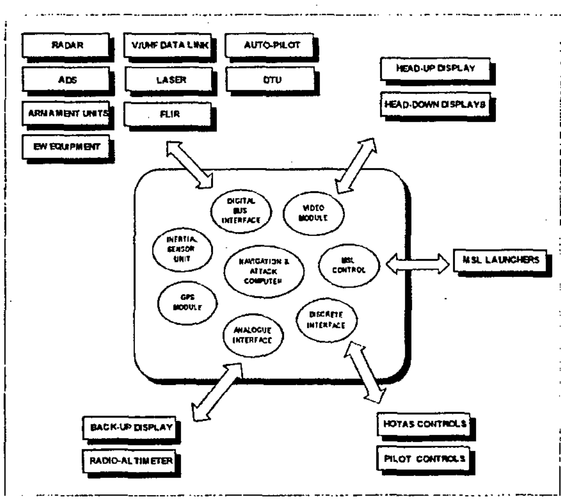
SAGEM INTEGRATED MODULAR AVIONICS APPROACH

The avionics system upgrade level can be evaluated, from the operational point of view, as the ability of the system to perform efficiently the mission for which it will be used. Given the great diversity of today's missions, the multi-role platforms are consequently the best operational solution for most of the armed forces. Today's combat aircraft has to be a polyvalent platform intended for upgrading.

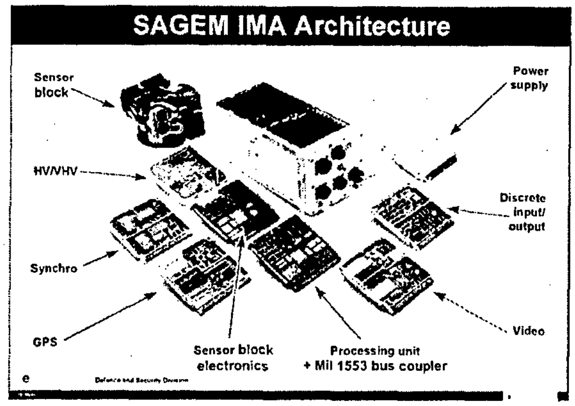
To upgrade a combat aircraft (old or new one) a modular and integrated logic is required in order to comply fully with the armed forces evolution requirements. In fact, according to today's economic requirements of the forces, the platforms which were initially designed and bought to perform a particular mission, will generally be modified or adapted to new missions which nature will be developed in accordance to the geopolitical situation of the countries involved. So, the initial operational requirements get more complicated and their time validity is reduced.

In order to meet this new requirement, the system architectures offered will have to be functionally open-ended and economically attractive: therefore, the Integrated Modular Avionics (IMA) concept is involved. This modular approach of SAGEM is considered as an original one because all the main management and control functions of the system are gathered in a single equipment (system core) with a standardized welcoming structure based on the inertial navigation system (INS).

In order to meet specific requirements, hardware and software system functions have been added to this core.



Mission Management and Navigation Unit



AVANTAGES OF THE SAGEM APPROACH

The navigation unit is usually used as a system sensor giving attitude and position data. Nevertheless, it is much more profitable to use it as a basic equipment for the MNAS development:

→ ***Optimal System Integration***

The whole management and control functions of the system are gathered in a single equipment entirely benefiting from the following hardware resources needed to operate:

- ❒ high-performance RISC computer used as a mission and navigation management system
- ❒ digital (ARINC 429, 1553B BUS, RS-422) and analog (Discrete, Synchro ...) interface modules
- ❒ symbol generator video module (HUD, MFD)
- ❒ an armament management module ("Store Management Module")
- ❒ a C/A or P(Y) GPS module

The origin of these modules can vary from one model to the other. They can be replaced easily for technology (for example, obsolescence of the components) as for functional reasons (to improve performances).

→ ***Higher performances***

As the main computer is the same for mission management and navigation, the delays for dating the parameters needed for ballistic calculations are reduced, thus providing an improved aiming accuracy.

→ ***A cost-effective solution***

As the number of equipment to be connected is lower, the cost of integrating the equipment into the aircraft is reduced as well. The aircraft wiring modifications are also reduced.

→ ***A reliable and upgradable solution***

As various electronic modules are gathered in only one equipment, with shared resources (power, mass storage, CPU, etc.), this system is more reliable compared to a classical architecture.

Moreover, the reduction in the equipment number leads also to the aircraft digital bus load reduction thus making easier to integrate new external sensors.

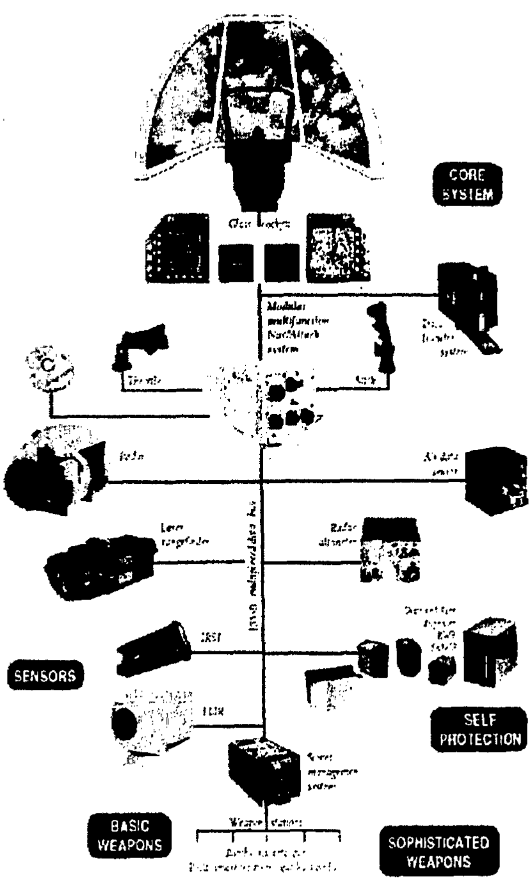
→ ***Easier maintenance operations***

The maintenance cost is also a key factor to select the right system architecture.

The reduction in the equipment number directly affects the maintenance cost by reducing as well the number of maintenance test benches.

SAGEM ARCHITECTURE EXAMPLE

As an example, a SAGEM integrated modular architecture is showed hereafter. The whole functions of the system have been centralized into a single equipment.



MANAGEMENT OF AN UPGRADE PROGRAMME

The IMA concept has a direct impact on the way to manage an upgrade programme. Generally, such programme can be made up of eight stages:

1- Detailed analysis of the operational need

According to the operational need, expressed first by the headquarters when applying to strategic options (armaments, Radar, EW Equipment, etc.) and then expressed by the pilots when applying to operational options (system interface), a relevant analysis stage is required in order to define the main upgrade axes while meeting the following requirements:

- cost-effective requirements (total budget)
- operational requirements (performances)
- aircraft requirements (mechanical loading, electric power, cooling environment, ...)
- customer requirements (logistic capacities)

The use of qualified technologies and integrated modular avionics (IMA) design is required so as to optimize the development cost and programme financial success by reducing the aircraft modifications and developments (hardware and software).

Defining a logistic support adapted to the customer requirements and capacities is also a deciding factor.

2- System design

The hardware design of the system has been simplified thanks to the integration of a modular avionics and the software design has been also simplified due to the operation of functional and qualified modules. However, with such an approach the system designer must think in terms of functional modules (hardware or software) and not in terms of equipment.

At the same time, an important work on the aircraft must be initialized at the beginning of the programme in order to identify as soon as possible all the aircraft requirements.

3- Software integration

This stage is dedicated to the integration and the validation of all software modules which have been gathered as single processing module. Specific software development and simulation tools have to be used at this stage to validate specific requirements (interface, timing, dynamic behaviour...)

4- System integration

Following the Software integration stage, all the functions and interfaces of the system have to be validated via a dedicated integrating test bench allowing to implement the real equipment as well as simulation models. This test bench is absolutely necessary to validate modules and to implement the system.

5- Integrating the equipment into the aircraft prototype model

The aim of this step is to integrate and validate the electrical and mechanical installations of the aircraft equipment and the specific part of the test instruments. It is also used to check the equipment environmental conditioning.

6- Ground and flight tests

The aim of this step is to verify the performances of the system and to prove to the customer that all the operational requirements have been fulfilled properly.

7- Preparing and starting production

In order to be successful, this preparation stage has to start during the modification of the prototype model so as to validate simultaneously the whole aircraft modification sheets (TCTO).

In order to reduce the costs, a partnership usually takes place with the customer for production (production of mechanical and electrical installation kits, equipment installation, etc.).

8- Integrated logistic support

The logistic support shall be defined according to the needs and capacities of the customer for the required levels (O, I and D'Levels). It generally includes the delivery of the spare equipment and test equipment, the training to maintenance, the maintenance documentation supply and, eventually the implementation of a local technical assistance team.

CONCLUSION

Due to the reduction of defense budgets, every aircraft manufacturer or system designer now understands that it is no longer possible to design complex systems by simply associating, as before, system function with an individual equipment. In order to satisfy the cost-effectivity, upgradability and accuracy needs of the air forces, integrated modular solutions are today's must.

Very early confronted with the market competition for military aircraft upgrades, SAGEM has developed an integrated modular core system implementing cost-reduction industrial processes, which can easily be tailored according to customers' requirements. This core system is based upon functional modules which are either developed by SAGEM or outsourced from specialised manufacturers. Today, this core system is in operation at the heart of several upgrade programmes.

Laser Designation Pod on the Italian Air Force AM-X Aircraft: a Prototype Integration

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Summary

The paper describes the prototype integration, on the Italian Air Force AM-X aircraft, of the Thomson Convertible Laser Designation Pod. The integration was conducted within the Italian Air Force Official Test Centre, and the process adopted was devised to produce a quick, low-cost, and low-risk sub-system integration. Software had the greatest part in the project, and software-engineering methods have been used to support the effort.
This integration is a good example of how a careful use of existing assets and experiences, together with the application of advanced software engineering techniques, can improve the effectiveness of an aircraft, keeping it up with the evolving needs. The integration is now being used as baseline by the aircraft manufacturer, thus reducing costs and times for the Italian Air Force.

Introduction

It is widely accepted that the key point in keeping up-to-date modern combat aircraft is no longer the airframe but the mission system. The airframes have a life that easily exceeds twenty years, while the mission systems rapidly become obsolete with respect to the ever-advancing state-of-the-art of the electronics and computers (Figure 1). The "mid-life update" is an already well-established term indicating a set of upgrades ranging from structural life extension to new radar, communication systems, navigation sensors, cockpit instruments, weapons. They are extensive and expensive processes, whose aim is twofold: substantial savings with respect to new designs (also due to simpler procurement processes), and aircraft with new or greatly enhanced capabilities. However, the availability of standard-interfaced, off-the-shelves sensors and the need of answering to the evolution of threats and tasks, pose the air forces with the problem to modify the mission systems more frequently. In addition, the key role played by the software in nowadays airborne systems offers new opportunities to execute upgrades of the combat aircraft without having large industrial facilities like those requested to modify or upgrade the airframes.

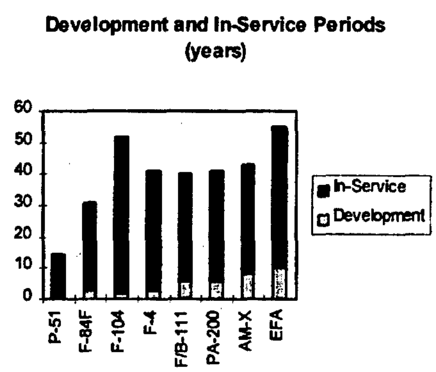

Figure 1 - Examples of aircraft operational life

As final users, the air forces are the best candidate to identify and analyse the new requirements to be implemented. Many of them have therefore developed in-house capability to study or to modify the software running on their aircraft. The Italian Air Force (IAF) is currently introducing into service the

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

final version of its AM-X light attack aircraft. In order to improve its capabilities, IAF considered various retrofits to the mission system, and, specifically, the integration of a laser designation pod, to provide the aircraft with a laser guided bomb self designation capability.

We describe the software aspects of the integration, by focusing mainly on the requirements engineering activities. The hardware modifications were in fact limited to those strictly needed to connect the laser pod to the AM-X avionics system RIG (i.e., power lines, data cables, and control switches).
In the early stage of the requirements engineering activities, aspects such as the final system goals, the feasible alternatives, the different and often clashing interests of the various people affected by the system (pilots, developers, etc.) are addressed. The objective of the late phase requirements engineering activities is to produce a requirement document that would specify and constrain the final system, therefore suitable to be adopted in a contractual setting. We used a *rapid prototyping technique*, by exploiting an evolutionary prototype to elicit and validate system requirements. The analysis and the validation of the requirements drove the evolution of the project into an *incremental method*, where the use of the prototype caused a continuous evolution of the requirements themselves. We dedicated great attention to the requirements capture and validation, by carefully assessing their relevance both for the operative situations and for the implementation. As final result, the prototype has become an "animated" and "validated" requirements document, yet a fundamental component of the final system.

The following part of the present paper is organised as follows. Section 2 briefly introduces the integration problem. Section 3 provides an overview of the proposed solution approach, and of its rationale Section 4 discusses the project results, by providing both qualitative and quantitative insights. Finally, Section 5 concludes the description of the work, by summarising the benefits of the adopted approach.

Integration Problem Overview

The Aircraft. The AM-X has been developed by an Italian-Brazilian joint effort to provide both air forces with an aircraft capable to deliver a medium load out of short or semi-prepared airfield, at a moderate distance and high subsonic speed. Design studies began in 1977, and IAF took delivery of its first AM-X in October 1989. The basic AM-X performance and weapons data are published in [1]; only some of them have been reported in Table 1.

Manufacturer	Alenia (Italy) Aermacchi (Italy) Embraer (Brasil)
Wing Span	9.9 mt
Length	13 mt
Height	4.5 mt
Wing Surface	21 mt2
Engine	Turbofan (without a/b)
Max. Speed	subsonic
Max. Height	> 12000 mt
Max. Range (ferry)	> 3000 Km

Table 1 – AM-X Performance Data

The AM-X mission system is a typical first generation 1553-bus (Mil-bus) design, built around a digital mission computer, which acts also as bus controller (Bus Controller/Main Computer - BC/MC). The mission subsystems and sensors are connected as remote terminals.

The Man-Machine Interface (MMI) of the mission system is designed around two main displays: a "Multifunctional Head Down Display" (HDD), with configurable function keys, and a "Head Up Display" (HUD). The HDD performs also part of the route and display computations, thus leaving more computational power available on the BC/MC.

The Laser Designation Pod. The laser designation pod selected for the AM-X is the Thomson Convertible Laser Designation Pod (CLDP) [2], already operative on the IAF TORNADO IDS, on the French Air Force JAGUAR and MIRAGE 2000.

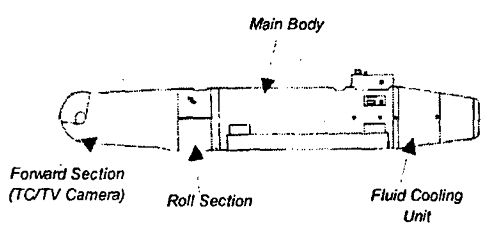

Figure 2 – The Convertible Laser Designation Pod (CLDP)

The CLDP (Figure 2) allows the aircraft crew to:

- visually acquire an on-ground target (the CLDP can be equipped with either a TV or Thermal camera, i.e. the Convertible capability);
- track the target (various internal algorithms are available);
- measure the target/aircraft distance;
- illuminate the target for subsequent weapon guidance.

Integrate the CLDP onto the AM-X. Despite the wide diffusion of similar systems, the integration of the CLDP on the AM-X posed upon us a new challenge.

The initial pre-feasibility study [3] (that prompted the acquisition of a prototype CLPD for the AM-X) had only defined the guidelines for the integration: the CLDP had to be used as a targeting sensor for the precision delivery of Laser Guided Bombs (LGB), and as a navigation sensor. The CLDP prototype integration project was therefore set off as a low-budget short-term activity aiming at (1) fully investigating the feasibility of equipping the AM-X with the CLDP, and (2) identifying an economical and low-risk integration solution. This kind of activities shows grey (or black) areas that generate risks for the project. Some risks are typical of the integration projects, some other are particular of this specific case, as discussed in the following.

Complexity of the solution space.

Finding a solution to the integration problem means to define a complete and consistent set of requirements that the new system (i.e. the aircraft equipped with the CLDP) has to satisfy. Only a minor set of these requirements concern technical (functional) aspects of the integration (e.g. the data the CLDP has to provide as navigation sensor); most of them are related to non-functional aspects. These regards both human factors, such as pilot workload, pilot performance, and situation awareness, and system quality attributes, such as safety, reliability, time and cost. In comparison with functional requirements, *non-functional requirements* are highly subjective (e.g. test pilots and front line pilots can have a different perception of the same problem), strictly related to the particular context, and more difficult to be discovered, stated and validated, without "interacting" with the final system. This increases the complexity of the solution space, introduces a certain degree of instability in the requirements, and makes difficult to compare different alternatives. However, being mistakes made at the requirements definition stage extremely difficult (and expensive) to recover during the subsequent system development, it is crucial, for the requirements engineering process, to be able to cope with such difficulties.

Complexity of the target platform

Although the AM-X mission system can be classified as a traditional one, it presents some elements of complexity. With regards to the stored data and to the functions offered to the pilot, it can in fact be defined as a distributed system. In other words, many of the functions in the mission system are performed via a co-operation of two or more subsystems. As a consequence, modifying or enhancing such functions requires operating on different equipment, which may adopt different hardware and software solutions (e.g. the used programming languages go from assembly, to Fortran, to Ada), requiring a broad range of skills not usually available in the same personnel. Moreover, equipment are often produced and maintained by different companies, so that the Air Force is faced with different levels of visibility, procurement processes and schedules.

Novelties of the Project

The basics of the Laser Guided Bombs operations were well known, thanks to the Tornado experience; but IAF specialists had still a limited inside knowledge of the AM-X mission system. In addition, it was the first example within the IAF of use of the CLDP on a single-seater aircraft.

Project Organisation

In order to reduce the associate risks, and to be compliant, at the same time, with the low-budget and short-term constraints posed on the project, it has been organised following some simple guidelines, that is:

- minimise modifications to the AM-X avionics system;
- exploit internal IAF resources and capabilities, i.e. personnel (test pilots and engineers, technicians) and equipment (low-cost avionics simulators and computers).
- re-use of previous experiences, both in terms of lesson learned and products. In particular, various projects regarding both the Tornado (among which the CLDP

integration), and the Italian Navy EH-101 helicopter[1] mission systems were carefully analysed, to identify requirements, algorithms, and software suitable to be reused and errors to be avoided.

In practical terms, this has led us to make precise choices regarding the *product* to develop, the *process* to apply, and the *team* to employ.

The Product. The integration of the CLDP to the AM-X avionics system asked both for new software and hardware. The new hardware was maintained to the absolute minimum: the on/off and laser safe/armed switches, the Mil-bus and the electrical signal/power lines. These new links were dictated by the CLDP, that was an off-the-shelves item.

We had more freedom for the design of the software architecture and for the allocation of the corresponding components onto the various computers of the avionics system.

We decided to concentrate in the HDD the software to control the CLDP, to minimise the number of equipment to be updated and to exploit the characteristics of the HDD itself. The HDD was in fact the newest equipment of the mission system, its Motorola processor provided the needed growth capability, and its software was written in Ada, the most advanced among the programming languages used on the aircraft. In addition, the HDD was ready to receive and display the images generated by the CLDP.

The software modifications to the BC/MC were instead limited to those strictly necessary to introduce some Mil-bus messages and to extend the navigation and attack functions, to employ the CLDP. For example, by enabling the BC/MC software to receive and use also data incoming from the CLDP, the correction of the position of the aircraft (i.e. present position fixing) can now be performed also using the CLDP (more versatile than the forward-looking radar or the simple on-top method). The new Mil-bus messages have been added to allow the CLDP to exchange data with the HDD. The BC/MC does not in fact perform any kind of control on the CLDP, but redirects the CLDP data to/from the HDD, and provides the HDD with basic data about the mission system (navigation, attack), and the aircraft (attitude, position, speed).

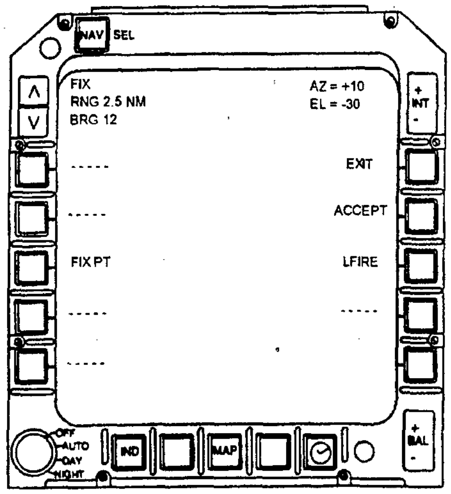

Figure 3 – Example HDD page for the CLDP

The HDD software has received only extensions. In particular: to handle the new Mil-bus messages [4]; to implement the required CLDP command and real-time control loop; to manage the CLDP pilot interface. The HDD software implements the pilot interface as a collection of cross-linked menu pages. By navigating through these pages, the pilot can access the various operations available: for example, synthetic maps, status of the equipment, and so on. For our purpose, the software has been extended to add some dedicated pages to control the CLDP. In other words, a new menu page has been devised for each main class of CLDP functionality. Specifically, it has been added a dedicated page to access/perform the various navigation operations (present position fixing, on-ground point acquisition), attack operations, testing operations, and so on. As example, in Figure 3 it is depicted in a simplified way the HDD page through which the pilot can perform a "present position fixing" employing the CLDP. By using this page, the pilot can select the fix point (FIXPT key on Figure 3), disable/enable the firing of the laser (LFIRE), read the position correction values (as range and bearing), and ACCEPT or EXIT the procedure. The Ada software architecture has been designed to obtain a high independence between the functions written to control the CLDP, and the functions implementing the interface. This allowed us to

[1] The EH-101, produced by UK WESTLAND and IT AGUSTA is a joint effort to produce a versatile multi-role platform for tactical transport, Anti-Submarine Warfare, Search And Rescue, and civilian transport.

produce stable software for the command and control, yet having the possibility to change the interface without impacting onto the deep (and more delicate) algorithms of the CLDP control. Whereas the definition of the final interface structure was obtained by continuously refining it with the pilot, the internal management of the CLDP and the used algorithms were an exclusive subject of discussion of the engineers. They worked using the Tornado experience and evolved them with a lower number of refinement cycles.

To conclude, in Figure 4 a simplified view of the chosen integration architecture is pictured. Here it is shown also the CLDP hardware control panel which provides, for example, the on/off and laser safe/armed switches.

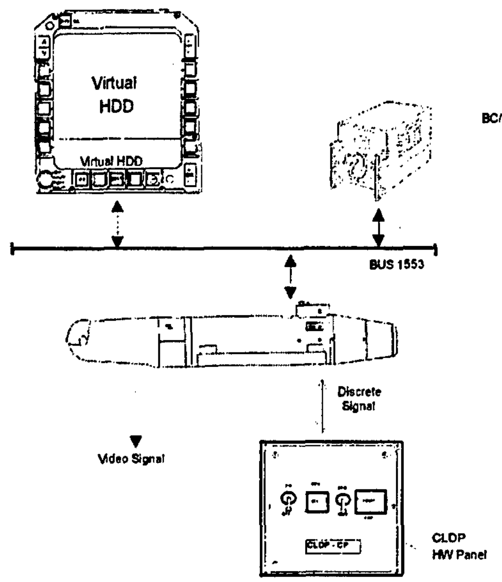

Figure 4 – Simplified view of the integration architecture

The Project Team. The project Team was organised in order to reduce as much as possible the number of involved people (and the corresponding co-ordination problems), and to exploit the available skills. Then, to increment the degree of concurrency between the different tasks to be performed, the project team has been divided up into 3 different sub-groups, with specific competencies, responsibilities and workload:

Software Development Team, with the task of managing the whole project and develop the necessary software, composed of 2 software engineers and 2 technicians. In particular, the group members worked together for the requirements, while each of them was dedicated to the single aspects of the ADA code, the Fortran code, the Assembler code and the operating systems.

Hardware Support Team, with the task of performing the CLDP hardware integration onto the AM-X avionics system and taking care of its maintenance, composed of 2 technicians;

User Group, with the task of collaborating the requirements elicitation and validation phases, composed of a test pilot and a Tornado test navigator. Both of them had specific experience with LGB operations, and were supported by front line pilots.

The Development Process. Two paradigms usually adopted within software engineering to reduce and manage risks associated with requirements instability and complexity have been adopted and customised: *rapid prototyping* and *incremental development* [5].

The classical software development approach (the waterfall model) is based upon a series of sequential stages that goes from requirements analysis, through coding and testing, to the system delivery. Here, it is assumed that most of the requirements can be defined at the outset of the project, whereas it is well recognised that requirements instability could easily lead to critical cost and schedule overruns.

Rapid prototyping is method a in which the exact opposite of the traditional software development approach is held true: time and resources are fixed, as far as possible, and the requirements are allowed to change. It is therefore suitable for all those cases in which the requirements cannot be exactly defined at the beginning of the development. For example, when the stakeholders do not have a clear idea of the system to be developed, but this will mature over time, or when different solutions seem to be equally valid and a deeper analysis appears to be necessary. To achieve its goals, rapid prototyping employs user-centred product prototypes, and requires a close collaboration between users and developers. Software prototypes come in different form, including throwaway prototypes, quick-and-dirty prototypes, and evolutionary prototypes, that is prototypes that evolve in the final system. The common idea is to allow the developers to rapidly construct primitive versions of the software system that the users can interact with and evaluate. The obtained feedback is incorporated to correct, refine, and enrich the emerging system properties.

In order to deal with the previously described complexity of the solution space, a rapid prototyping techniques has been adopted to perform our integration study. In particular, rather than developing the CLDP control software directly on the HDD, an evolutionary prototype of such software has been developed. This software model (thereafter referred to as *Virtual HDD*) gave us a powerful tool for the requirements analysis at an early stage, that was usable throughout the full life cycle of the software (evolutionary prototype). The virtual HDD has in fact allowed us to enrich our avionics RIG with the CLDP, and then use the RIG analyse the CLDP operating procedures with the members of the User Group.

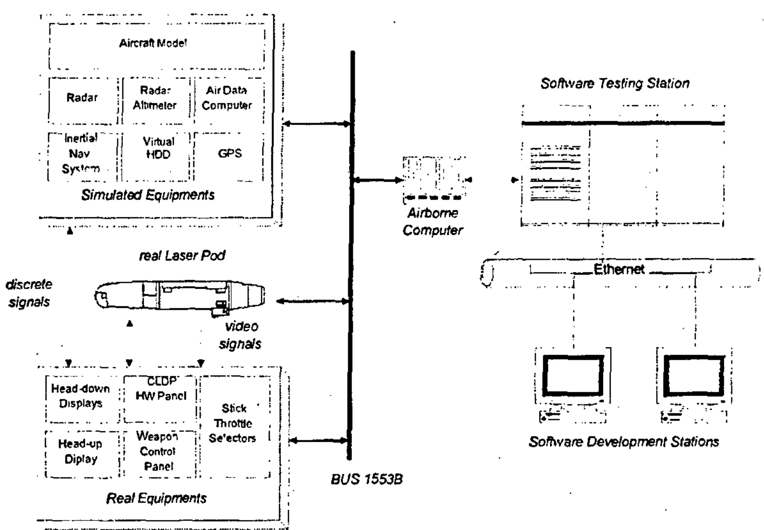

Figure 5: Architecture of the Avionics RIG

A simplified scheme of the architecture of the AM-X Avionics System RIG (ASR) used through the integration study is illustrated in Figure 5. Apart from the Software Development Stations and the Software Testing Station, used to modify the airborne software and test it directly on the BC/MC, the ASR consists of a mixture of real and simulated equipment. For example, while all the main sensors are simulated (Inertial Navigation System, Air Data Computer, Tacan, etc.), a real CLDP is used, together with real units associated with the AM-X mission system MMI (HDD, HUD, switches and selectors, Pilot Stick and Throttle). The MMI allows a pilot to form part of the overall rig, so that the effects of the proposed new weapon system on pilot performance can be determined. It is worth noting that in order to reduce the costs associated with ASR development and maintenance, the ASR has been designed to provide only the capabilities strictly necessary to perform the integration study. The absence of more complex features, as, for example, a wrap-around display to represent the external world, has been overcome by employing especially trained personnel.

The simulated subsystems are realised using a high-level testing tool, i.e. the AIDASS, by ALENIA. It consists of a set of real time VAX computers inter-linked via a VME bus, and equipped with the interfaces necessary to be connected the AM-X avionics system (Mil-bus, discrete and analogue signals). Both the aircraft simulator and the set of sensor simulators have been developed within the IAF Operational Test Centre, by partially customising software created for other projects. As the other simulated equipment, also the Virtual HDD was implemented on the testing tool AIDASS. This not only gave us the possibility of using the Ada programming language (the same adopted in the real HDD) that, combined with an ad-hoc design, allowed us to obtain a software package immediately portable on the real HDD, but also of employing an advanced environment for software debugging.

Although rapid prototyping is a good solution to deal with unstable requirements, it is difficult to apply on big projects, and can easily lead to an explosion of project complexity, and associated risks, whenever requirements instability is not confined to a specific area. For such a purpose, an *incremental development* approach has been adopted in conjunction. In other words, in order to reduce and manage project complexity, the initial "unstable" set of requirements have been divided up into three sub-sets, that is:

- the sub-set A, regarding the CLDP basic control functions (e.g. test functions, CLDP pointing, etc.), and implementing the CLDP interface control document;
- the sub-set B, regarding the integration of the CLDP with the aircraft navigation functions;
- the sub-set C, regarding the integration of the CLDP with the aircraft attack functions.

In Figure 6 it is schematised the software development process adopted to perform the integration study, especially devised to combine the benefits provided by the rapid prototyping and the incremental development techniques.

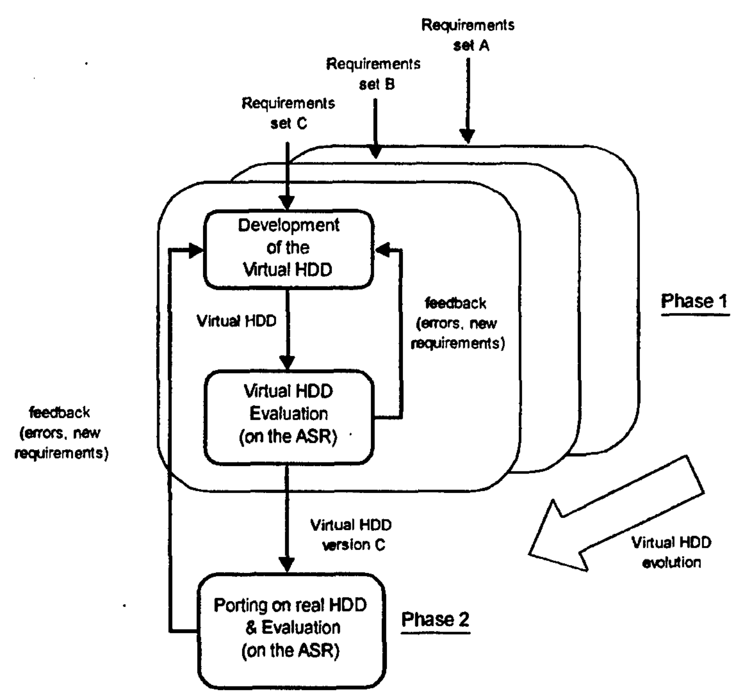

Figure 6: The adopted development process

As shown in Figure 6, such a process is based on two main phases.

During the *phase 1*, the virtual HDD was developed. In particular, first, the Virtual HDD was built by fully developing the sub-set A of the requirements (Virtual HDD version A), then by introducing the sub-set B (to obtain Virtual HDD version B), and finally by introducing the sub-set C (to obtain the Virtual HDD version C). After being developed, each version was evaluated by employing the ASR. The evaluation was performed mainly by the User Group, which was involved in order to validate, correct or improve the requirements already implemented, and to discover new requirements. Depending on the results of this evaluation, more correction and refinement loops occurred. Only when the version C of the Virtual HDD resulted to satisfy the users needs (i.e. the Virtual HDD was a full representation of the desired final system), we passed to the *phase 2*. Here the software implementing the Virtual HDD was ported on the real HDD, and, this, on its turn, was evaluated. As final result, the modified HDD became an "animated" and "validated" requirements document, yet a fundamental component of the final system.

Having defined the development process, we were able to clearly identify and separate the efforts of the various sub-groups of the Project Team, increasing the concurrency within the different project tasks and between this project and other projects. Moreover, the HDD manufacturer was involved to modify the real HDD only at a late stage, when a stable idea of the final system was available, reducing the associated costs and schedule.

The described process regards the development of the software for the HDD. Due in fact to the small amount of changes required by the software of the BC/MC, a more traditional approach was applied in this case. In particular, the BC/MC software was modified to follow the evolution of the Virtual HDD, and to allow its integration on the ASR.

Project Results

Single-Seater or Two-Seater? IAF opted for the CLDP modification to be used by the single-seater version of the AM-X. On the other hand, LGBs are used onto other single-seater (e.g. the French JAGUAR [2]).

The presence of a single crewman faced us with a set of requirements that were not present on the Tornado, where the navigator can dedicate himself to the CLDP operations. We answered to these requirements in two steps:

- a more careful construction of the "Operator Dialogue" (i.e. the sequence of buttons to be pressed to obtain a function) of the MMI, in order to make the use of the CLDP as simple and straight as possible, without reducing the number of available functions;
- a set of facilities to lower the workload of the pilot and to enhance the safety of the operation.

The MMI was implemented by using at the maximum extent the available HOTAS (Hands On Throttle And Stick) commands (e.g. the CLDP LOS is controlled via the same joystick, placed on the throttle, that is already used to point the Radar Antenna). Moreover, to allow the pilot to point the CLDP, looking either inside or outside the cockpit, we used a cross symbol already available on the HUD to mark the same spot looked at by the CLDP camera.

In order to keep low the risks induced by the pilot looking inside the cockpit, at the HDD, an essential attitude indicator is superimposed to the CLDP image, along with alert messages (e.g. "ROLL OUT"), should some basic aircraft attitude, speed or terrain separation limit be violated. The presence of the automatic pilot, and the philosophy of LGB attacks, that foresees medium-to-high-altitude attacks in a context of air-superiority, also support the viability of the single-seat use.

Nevertheless the CLDP modification is immediately portable and fully compatible with the two-seater version of the AM-X. The two-seater will offer the advantage of a dedicated crewmember for the management of the laser pod. It will allow an effective training at low risk, and, also, "co-operative attacks" (one illuminator ship, more carrier ships), for which a dedicate crewmember is deemed essential.

2 The JAGUAR uses the same CLDP pod, but it can deliver the AS-30 missile, with a greater stand-off range with respect to the LGBs used by the AM-X.

Quantitative Insights. The final size of the produced software is of 9000 Ada LOC (Line Of Code) for the HDD, and 300 Fortran LOC plus 150 Assembly LOC for the BC/MC. The relative impact of the modification with respect to the total software is low (Table 2). This is a welcome property, which keeps low the risk of introducing new defects and reduces the work of re-evaluating and testing the existing functions.

Airborne Computer	Modified Software	New Software
BC/MC	2%	1%
HDD	1%	15%

Table 2 – Percentages of Modified and New Software

On the basis of the development process described in the previous Section, a more detailed analysis is possible.

The initial release of the Virtual HDD (version A), consisting of about 5500 Ada LOC, 200 Fortran LOC, and 150 assembly LOC, was produced in about 7 months. The personnel involved were, initially, only the members of the Software Development Team. Once the confidence into the technical feasibility of the project was achieved, the User Group was involved to deal with the operative requirements, while the Hardware Support Group updated as required the ASR. Then the first period of evaluation, debug, and re-evaluation of the model was performed.

Having reached a stable version A, we started introducing the sub-set B of the requirements. This phase lasted about 5 months. Then we started the integration of the sub-set C of requirements. The phase ended after about 3 months, therefore the version C of the Virtual HDD (about 10000 LOC, airborne code plus some ancillary code for the RIG) was produced in a 15-month period.

The porting of the Virtual HDD version C onto the real HDD was straight. The only exception was a fine parameterisation of the code due to the different way of numbering the bits within a word, used on the VAX of the virtual HDD and on the Motorola microprocessor of the real HDD. For the porting, two people from the HDD manufacturer were involved, for a limited number of meetings and for a total of 6 days of actual integration. As further confirmation of the quality of the Virtual HDD, and of the adopted development process, the evaluation on the ASR of the modified HDD revealed only some minor defects.

The effort, duration and size of the project are well estimated by the Constructive Cost estimation Model (COCOMO) [6], as illustrated by Table 3, where, for the sake of brevity, only the main results obtained by applying such an estimation tool are reported.

The delay of the project with respect to the schedule provided by the COCOMO equations (about 5 months) is due mainly to pre-emption of personnel for other tasks (about 3 months), and to some bureaucratic delays with the partner industries (about 1 month). In addition, the team was smaller than the estimated one.

Size	10,25 Kilo delivered LOC
Effort	76,02 Man-Month
Schedule	9,99 Months
Average Team Size	7,60 Persons

Table 3 – The COCOMO Model applied to the AM-X / CLDP Integration case

Costs. The costs of our integration study are low, mainly due to the project having been run with in-house resources (personnel and low-cost RIGs), and a small support from the partner industries.
The recurrent costs are quite low, being limited to the reload of some software packages, and to the introduction of the CLDP on/off switch, power supply cables and connectors. The CLDP are basically those already available for the Tornado, so the costs of the logistics can be shared with the other aircraft.

Enhancement of Capability. The need for precision attacks from high altitude dramatically emerged in the current scenarios of peace keeping/enforcing operations, where "surgical" attacks are needed. IAF also needed to enhance the effectiveness of each single aircraft, in a context of a shrinking budget.
The CLDP is a viable answer to the above problems, therefore the benefits/costs ratio of it should be considered high just for operative reasons, also without taking into account the economical advantages of our implementation.

Conclusions

We described a prototype integration of a laser illumination pod onto the AM-X aircraft, in the context of a low-cost, high-confidence-of-success project.

Software can be changed without large industrial facilities and software upgrades can greately enhance an aircraft performances. Our solution was a software modification at 95%, and made large use of software engineering techniques to quickly obtain the desired results at low costs. We consider our experience as positive and successful. The general guidelines emerging from it are the following:

- consider using off-the-shelves equipment and modification of the software, to match new requirements in a cheap a viable way;
- exploit the capacity to blend legacy or available systems and new devices in the path of reducing costs and time;
- use tight collaboration among industry, operating people and engineers of the Air Force;
- employ small, committed groups; with a clear and realistic scope;
- be aware that bureaucratic problems are independent from the complexity of the technical problems. They are functions of the visibility of the project and of the number of groups involved;
- use simulation for assessment & evaluation, but use the real software and hardware for the finalisation of the work, to avoid duplications, delays and costs.

Acknowledgements

We would like to thank all the people that made this project possible, and, in particular, the persons who were directly involved in performing the work: Luca Attias, Marco Cittadini, Mario Solaro, Paolo Calabrese, and Marco Berardinetti.

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Achieving Helicopter Modernization with Advanced Technology Turbine Engines

(April 1999)

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I. Introduction

Military and commercial helicopter operators worldwide are faced with a common dilemma—when to replace existing fleets with newer, more capable, and yes, more expensive helicopters. Alternatively, how often and how much should they spend on upgrades. Either decision may be based on operational needs, operational support costs, or a combination of both.

On a personal level, you go through a similar process when deciding to replace the family car with a new or used car. As long as the basic mission remains unchanged, such as the daily commute to and from work, and the vehicle is reliable and replacement parts are readily available, then you probably can't economically rationalize a new car.

Automobile upgrades are virtually limitless as there are many sources for new engines, radios, security systems, power door locks, stereo systems, cruise controls, trailer hitches, and fog lights, among others. All of these options serve the same purpose: to make an existing car more functional or to extend its life.

A replacement can be rationalized when repair costs become too expensive, you experience a major failure, the car is no longer reliable, fuel costs or fuel consumption become prohibitive, or there is no longer room for the growing family.

Likewise, there are many examples where helicopter replacements are necessary in lieu of upgrades. Helicopter replacements are appropriate when the mission need and capability of the replacement is so compelling that upgrades to the existing system are simply cost prohibitive and/or the desired performance is not achievable within the existing airframe structure. Crashworthiness, cargo volume, night/adverse weather capability, payload, range, speed, battle damage vulnerability, multi-engine requirements, and marinization, among many other considerations, might contribute to the replacement decision.

A few examples of cost and mission effective replacement helicopters are listed in Figure 1. The replacement of the CH-46 helicopter with the V-22 Osprey tiltrotor is the most compelling example of an extraordinary aircraft capability redefining an operational mission.

Legacy Helicopter	Replacement Helicopter
• UH-1H Huey	UH-60 Blackhawk (USA)
• AH-1S Cobra	AH-64 Apache
• CH-46 Sea Knight	V-22 Osprey
• UH-1H Huey	NH-90 (Germany)
• OH-58D Kiowa	RAH-66 Comanche

Figure 1. Replacement helicopter programs.

A decision to extend the life of a helicopter is appropriate when the mission has remained relatively unchanged and technology is available to directly enhance mission effectiveness (for example, communications and navigation equipment, survivability equipment, signature reduction, or helicopter performance). As always, available funding could be the controlling factor in spite of mission needs.

The U.S. Government achieves significant helicopter updates through programs such as Horizontal Technology Insertion (HTI) and "Modernization through Spares" programs. A communication package developed for the UH-60 under HTI may be applied to one or more other helicopters which helps to spread the development cost, reduce the production unit costs, lower support costs, and ensure standardization and interoperability. Likewise, modernization through spares takes advantage of new materials, electronics, or manufacturing processes to produce more reliable and longer lasting parts. In both cases, the greater the number of applications, the lower the unit cost.

Examples of successful helicopter upgrades are shown in Figure 2. The addition of the Longbow radar to the AH-64 Apache represents the greatest operational improvement achieved through technology insertion or a midlife upgrade program among the examples shown.

Legacy Helicopter	Upgraded Models
• CH-47A	CH-47B, C, D, E
• UH-60A	UH-60B, Q, L, L+, X
• AH-64A	AH-64B, C, D
• AH-1G	AH-1F, S, Q, W
• UH-1N	UH-1N (4BN)
• OH-58A	OH-58C, D, Armed
• A-129A	A-129I
• Lynx	Super Lynx
• S-76A	S-76B,C
• B206	B206III
• AS365	EC155

Figure 2. Helicopter upgrade programs.

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

The number of worldwide upgrades across all helicopter models far exceeds the procurement of replacement helicopters. Clearly, extending the life of current helicopters is far more cost effective than wholesale replacements and, in most cases, nearly as mission effective. With continuing budget shortfalls to operational requirements and exceedingly long timelines to field new helicopter systems, we can expect this trend to continue.

II. Turbine Engines and Helicopter Upgrade Programs

Although the number and type of helicopter upgrades available are limited only by the number of subsystems, the operational requirements, and the available funding, this paper will focus on the contribution of modern turbine engines to upgrade programs.

Significant improvements to fielded helicopters are realized through the installation of improved gas turbine engines with greatly increased power/weight ratios, reduced specific fuel consumption, and digital engine controls. Modern engines are operating at ever-increasing pressure ratios possible through the increased fidelity of computer modeling of compressor and turbine aerodynamics. Modern directionally solidified and single crystal turbine blades considerably enhance the engine temperature capability.

Electronic controls have simplified the engine's fuel control system since numerous pneumatic and fuel lines required for engine operation are no longer required. Operators also benefit from cooler and automatically controlled starts. Pilot's like automatic limiting, precise rotor control, and improved handling qualities.

As shown in Figure 3, helicopters, as a general rule, increase in maximum gross takeoff weight (MGTOW) over their operational lives. These increases are a direct result of increasing demands on operational capability. Accordingly, increasing takeoff weights demand more installed power to retain or improve operational performances. The RAH-66 is unique in that mission demands dictated an MGTOW increase prior to its fielding.

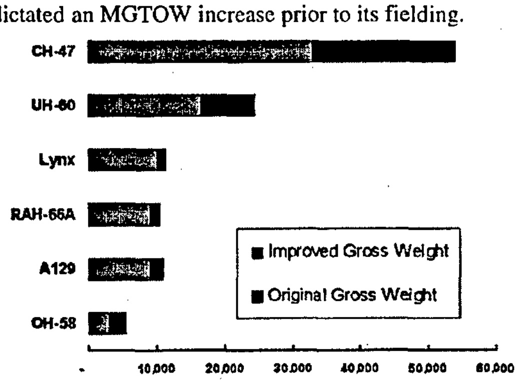


Figure 3. Gross weight increases demand increased power.

As helicopters grow in mission capability, engines are also continually improved over their lives to meet or exceed operator demands. Eventually, as military needs change, a government program will result in a new engine that provides a new baseline for incorporation of all technology currently available. In addition to technology insertion, these new engines feature modularity, marinization, electronic controls, and maintainability features in the baseline design. Current examples are the MTR390, RTM322, and T800.

MTU/Turbomeca/Rolls-Royce MTR390

The MTR390 was developed as a compact, rugged, and high performance engine for European civil and military helicopters in the 2.5 to 7.5 ton weight class. For the Eurocopter Tiger, the engine is rated at 1285 shp for takeoff and 1170 shp continuous.

Developed in the late 1980's, the MTR390 engine shares many features with the T800. The MTR390 consists of three modules including an integral reduction gearbox, gas generator, and power turbine.

The engine is controlled by a single channel full authority digital engine control (FADEC) with manual backup. Maintenance is performed on-condition with a minimum number of hand tools.

Roll-Royce/Turbomeca RTM322

The RTM322 was developed to compete in the 2100 to 3000 shp market as a modern technology engine. The development was initiated in 1983, and the RTM322 has been selected to power the EH-101 Merlin helicopter, WAH-64, and NH-90. Other potential applications include the UH-60 Blackhawk and Sikorsky S-92. The engine is a fairly simple alternative or replacement for the General Electric T700 since they share several applications (EH-101, NH-90, and AH-64) plus the RTM has been successfully demonstrated on the UH-60 Blackhawk.

From a technology standpoint the RTM322 is very similar to the T800, as I discuss later. Incorporating a modular design, the RTM322 engine consists of five modules including the inlet particle separator, compressor and intake, gas generator and combustor, and the power turbine. The engine was designed to provide better performance than competing engines and have growth potential to over 3,000 shp. As with most modern technology engines, the RTM322 is controlled by a dual channel FADEC, and features a very simple installation and significantly reduced pilot workload.

Since the engine was envisioned for marine operations, a high efficiency inlet particle separator is incorporated along with material and coatings that are resistant to corrosion. Installation in existing helicopters has been easy as in the case of the AH-64 for the United Kingdom Ministry of Defence described later.

LHTEC T800

The T800 engine was developed by the Light Helicopter Turbine Engine Company (LHTEC), a partnership of Rolls-Royce Allison and AlliedSignal.

The T800 is one of the world's most modern and technologically advanced gas turbine engines. It has a 4.1 power/weight ratio and the lowest fuel consumption of any turbine engine in its class. It is designed with self-contained and totally independent fuel, lubrication, and electrical systems and an advanced inlet particle separator with demonstrated sand-air separation efficiencies as high as 97.5%. The FADEC improves acceleration, minimizes rotor droop, and significantly reduces pilot workload through automatic starting and control of all engine, transmission, and rotor operating limits. The engine was designed for a 6000-hour life and "on-condition" maintenance without time-limited overhauls.

All of the turbomachinery performance was achieved through extensive development testing and use of the latest computational fluid dynamics codes. A patented device for the compressor provides improved off-design efficiency and stability margin. The power turbine module, FADEC, and all accessories are fully field replaceable.

III. T800 Engine Upgrade for the UH-1H

General

To illustrate the potential of engines to improve operational effectiveness in a cost-effective manner, the UH-1H helicopter upgraded with the T800-LHT-801 engine will be examined in detail. The UH-1H has been in worldwide operational service well beyond 30 years, while the T800 is one of the world's most modern turboshaft engines. Because of the contrast between a very old helicopter and very new engine, this best illustrates the operational value of engine technology at an affordable cost. The T800 engine was developed for the U.S. Army's RAH-66 Comanche helicopter (see Figures 4 and 7).

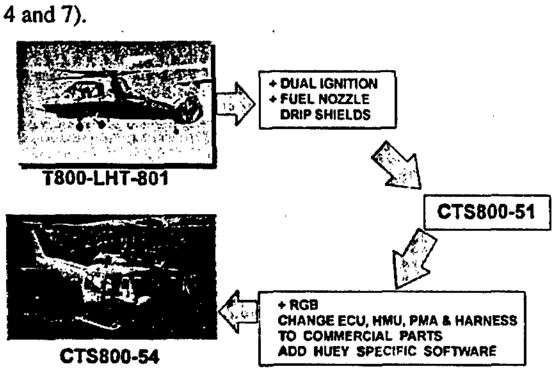


Figure 4. T800 configuration for UH-1H.

This example is also appropriate and very timely because the U.S. Army has just completed an exhaustive study which validated the cost effectiveness of this installation when compared to over 30 alternate helicopters or helicopter combinations. After the UH-1H example, several other engine upgrade and helicopter modification programs with their resultant performance gains will be summarized.

T800 Engine Description

An appropriate beginning is to agree on what is meant by an "advanced technology" engine. Technological measures include but are not limited to those listed in Figure 5. The T800 engine embodies all of these technologies and was specifically designed for outstanding operational performance, a very long life, ease of maintenance, and lower direct operating costs.

- Electronic Record Keeping, Scheduling, Diagnostics, and Training
- Advanced Materials for Durability and Weight Savings
- Modular Construction for Ease of Maintenance
- Higher Internal Temperatures and Pressures
- Reduction in the Repair Touch Labor
- Employment of Electronic Controls
- Elimination of Variable Geometry
- Higher Power-to-Weight Ratio
- Human Factors Considerations
- Engine Weight Reduction
- Lower Fuel Consumption
- Reduced Part Count
- Inlet Protection

Figure 5. Technology measurements.

As shown in Figure 6, all T800 technological achievements were driven by customer demands. In fact, the T800 engine development program responded to the most demanding system specification ever written for a turboshaft engine in this power class.

An overview of the T800 engine configuration is shown in Figure 7. Its simple architecture employs counter-rotating gas producer and power turbine shafts, two bearing supports, front drive, and through-flow gas path. Note how all accessories are located on top of the engine for reduced vulnerability and improved accessibility. The scroll shaped device in the outside view is part of the scavenge system for the inlet particle separator.

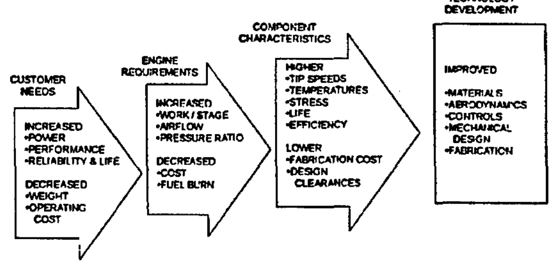


Figure 6. Customers drive design, materials, and technology.

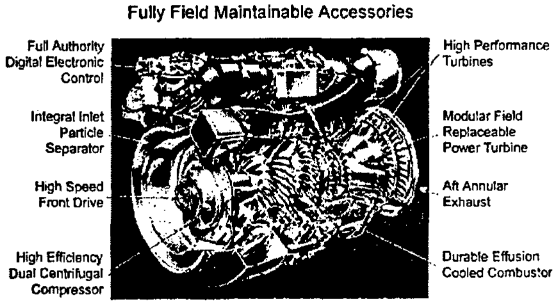


Figure 7. T800 engine configuration.

The main features of T800 core components are listed in Figure 8. All of the turbine disks are made of very high strength Udimet 720 material to reduce weight and inertia. Life of components is generally in excess of 15,000 cycles and 6,000 hours. The annular combustor is of the foldback type that minimizes the engine length and has special features that produce low gaseous emissions and smoke. Achieved performance surpasses the goals for all of these components.

T800 Development Program

The T800 development schedule is shown in Figure 9. Development of the engine began in 1984 with a U.S. Army qualification and Federal Aviation Administration (FAA) certification of the initial engine version, the T800-LHT-800, in 1993. As a result of lessons learned from Desert Storm, the mission weight specification for the RAH-66 Comanche increased, necessitating a 17% engine growth program to retain its mission performance. Development of the T800-LHT-801 engine began in 1993 and FAA certification is planned for 1999.

Maintenance Enhancements

The T800 is the first engine designed for two levels of maintenance, a greatly reduced number of tools, ease of maintenance in extreme conditions, and rapid completion of maintenance tasks. Removal and replacement of line replaceable units (LRUs) are the only organizational maintenance requirements. All engine/component repairs are accomplished at the depot level, thus eliminating a major investment in manpower and materials previously necessary to provide an intermediate maintenance capability.

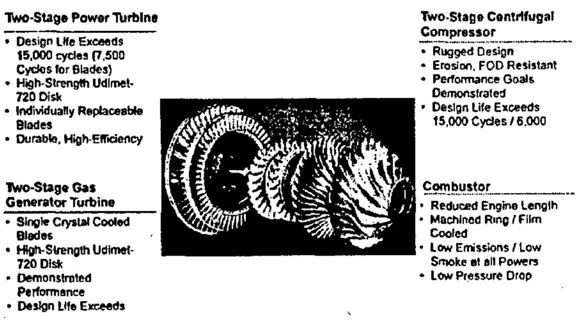


Figure 8. T800 core design.

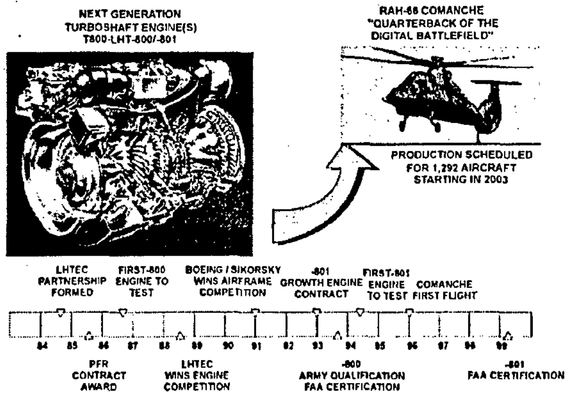


Figure 9. T800 program overview.

Maintenance man-hours have also been significantly reduced. Demonstrated maximum removal and replacement times are 34 minutes for modules and 12.8 minutes for all line replaceable units using six common hand tools (see Figure 10). The T800's modular construction consists of the gas producer, power turbine, inlet particle separator, and accessory drive system. It is important to note that the engine uses no safety wire.

Description of the UH-1H

The UH-1H "Huey," shown in Figure 11, is the world-renowned light utility workhorse having been produced in substantial quantities during the Vietnam war. It is estimated that over 5,000 helicopters are still in service around the world with nearly 1,000 still in the U.S. Army inventory.

The UH-1H has participated in every major conflict since Vietnam and, in fact, flew 85% of all aeromedical evacuations (MEDEVAC) during Desert Shield/Storm. It is by far the world's most cost-effective and dependable light utility helicopter. Because of its continuing and cost-effective relevancy to military missions worldwide, it is well suited for an engine upgrade. As previously mentioned, the U.S. Army, after considering all replacement alternatives, has chosen the UH-1H, with an engine upgrade, to fulfill its Light Utility Helicopter Mission until 2025.

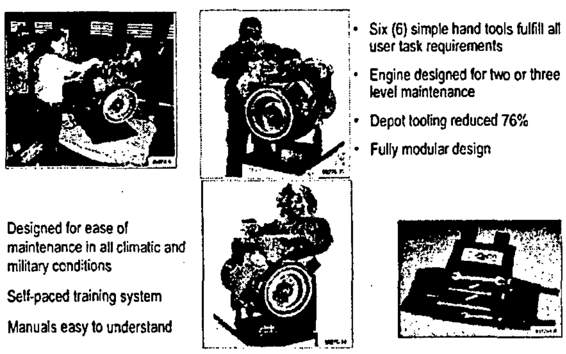


Figure 10. T800 is designed for maintainability.

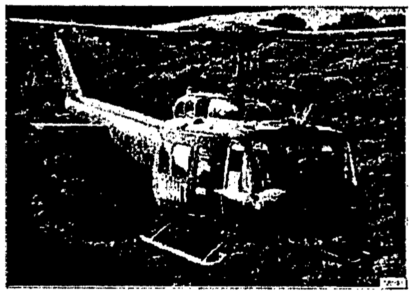


Figure 11. T800-powered UH-1H Huey.

The UH-1H remains an ideal helicopter for combat service support missions such as resupply and MEDEVAC, and for all peacetime operations such as disaster relief, drug interdiction, surveillance, administrative support, command and control, search and rescue, and other humanitarian missions. This is not to suggest that the UH-1H should perform combat assault missions for which there are far more capable helicopters such as the UH-60 Blackhawk. Conversely, it is not cost effective to use limited combat resources to perform "rear area" LUH missions because of their inherent complexity, cost, and performance.

The UH-1H airframe has demonstrated an indefinite life, with some airframes having accumulated over 30,000 flight hours. In comparison, the average hours on the current U.S. Army fleet is a very young 4,000 hours. The average hour profile will be even less once planned force structure reductions are implemented, since the Army will retain its newest and lowest flight time aircraft.

The only documented problems with the UH-1H helicopter are its engine and avionics, which are both easily and economically replaced.

Advantages of installing the T800 engine in the UH-1H are numerous, but there is an overall emphasis of minimizing the pilot's workload and enhancing helicopter performance. These features include automatic start sequencing and control, automatic and precise rotor speed control even during extreme maneuvers, flameout detection, and automatic reset to contingency power, if required.

A key performance objective to ensure agility and maneuverability for helicopters is a rapid power change. The -801 FADEC has been tuned for rapid engine acceleration. From flight idle, full power is available in just 3 seconds. A low inertia two-stage gas producer turbine and robust stability margin are the keys to rapid acceleration. Its response is so impressive that pilots have reported the perception of "extra" power.

Pilot workload is further reduced through the elimination or modification of several emergency procedures including engine restart, high/low side governor failure, droop compensator failure, short shaft failure, emergency governor operations, engine compressor stall, and overspeed.

The monitoring feature of the control system tracks parts life, records engine exceedances, fault diagnostics, and performance trending.

UH-1H Performance

Fuel consumption is so low that mission endurance is improved by over 50%. Other operational enhancements include significant improvements in payload, range, and endurance. As shown in Figure 12, the T800 is able to lift an additional 1,400 lb of payload—a 54% increase—with the existing airframe on a hot day at sea level.

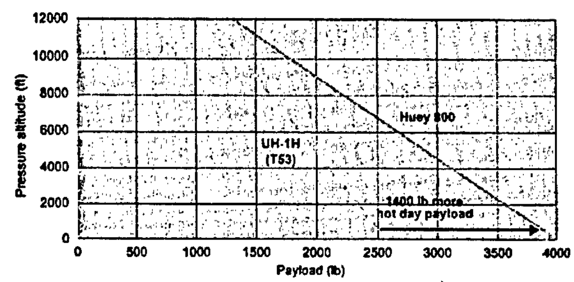


Figure 12. Hover performance (out of ground effect ISA +30 deg).

The T800 engine takes full advantage of current UH-1H dynamic component and structural limitations. Therefore, dynamic component upgrades (transmission, main rotor, tail rotor, and gearboxes) to the UH-1H are not justified by U.S. Army requirements.

A 58% range or 47% payload improvement is achieved with the current fuel load and existing airframe at 2,000 ft on a tropical day (see Figure 13).

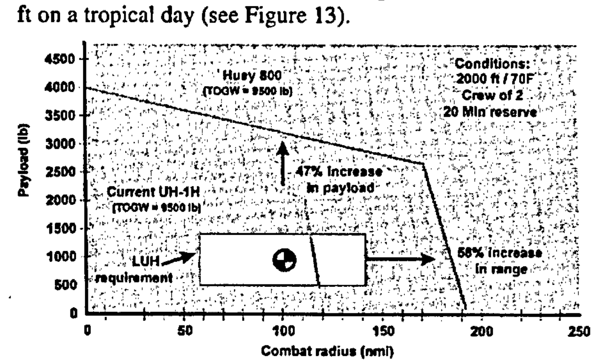


Figure 13. Payload/range comparison.

A dramatic demonstration of T800 performance occurred on April 22, 1993. A T800-powered UH-1H flew into the record books between Oxnard, California, and Atlanta, Georgia, shattering an unrefueled world distance record by over 600 statute miles. The distance of 1,975 miles was completed in just over 13 hours. The fuel burn on this 13-hour flight averaged only 311 lb per hour and as low as 220 lb per hour (see Figure 14).

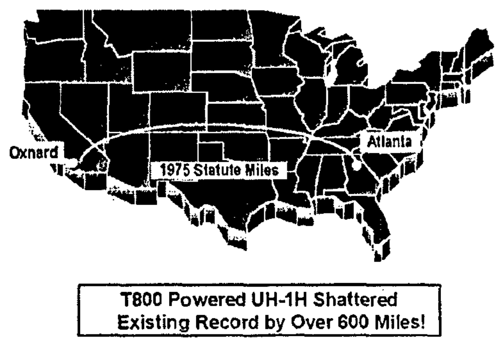


Figure 14. Huey 800 holds world distance record.

Installation

Installation of the CTS800-54, a commercial version of the T800-LHT-801, in the Huey is very simple and straightforward, as shown in Figure 15. The engine fits on the same mounts as the T53 and claims a smaller space. Note the speed reduction gearbox mounted on the front face of the engine and connected to the transmission short shaft.

With a sea level standard takeoff rating of 1575 shp, the CTS800-54 engine has 12.5% greater installed power than the T53 yet the T800 system weight is 144 lb lighter than the T53. This is another tribute to its high power/weight ratio, which translates directly into more payload or fuel carrying capability.

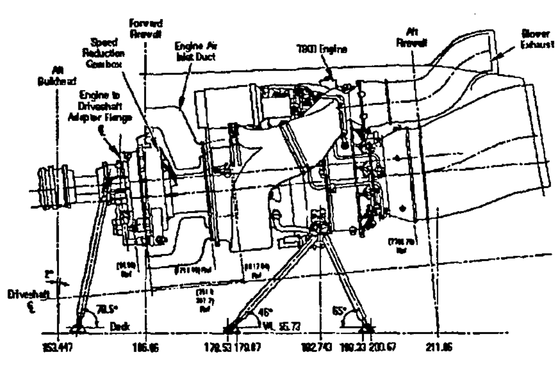


Figure 15. Simple, straightforward installation.

Investment

As shown in Figure 16, an operator will be able to recover the cost of a T800 installation through savings realized from as little as two T53 overhauls. The figure assumes that new engines are scheduled for installation as the T53 approaches an overhaul interval such that the full life of the T53 will have been realized. The overhaul savings are then deducted directly from the T800 initial acquisition cost.

The total savings achievable will vary significantly across worldwide support centers. It is also important to note that cost savings from an upgrade can only be realized through proper utilization of the operational fleet. Logically, the more hours the helicopters are flown, the faster the payback.

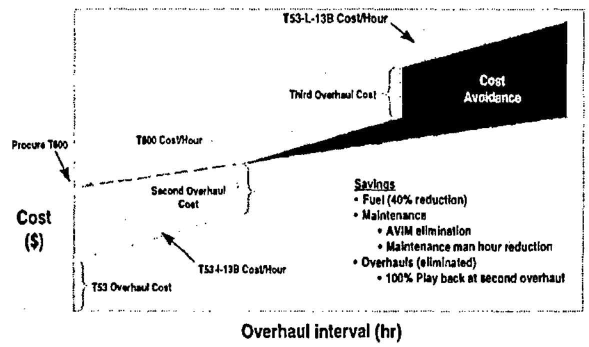
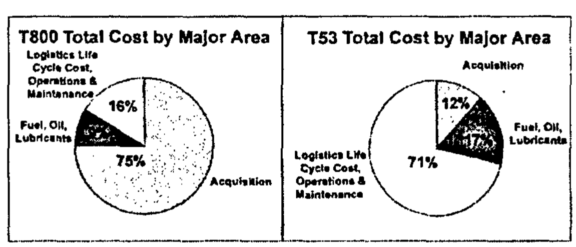


Figure 16. Investment (notional).

Figure 17 shows that the total capital outlays for the engine will remain essentially the same over a 20-year period. As shown, acquisition costs for a new engine are traded 1:1 for current support costs. In this worst case scenario, the performance gains would accrue to the operator essentially free of charge.



74% Reduction in Operations and Maintenance Cost

Figure 17. Total cost comparison.

Conclusion

By almost any measure, operators of the UH-1H helicopter would benefit significantly from an upgrade to the CTS800-54 engine. This example illustrates the improvements resulting from a 30-year leap in technology. The incorporation of a new engine will maintain the viability of the UH-1H helicopter well into the 21st century.

IV. Examples of the Engine Contribution to other Helicopter Upgrade Programs

Other modern helicopters have evolved from less capable beginnings. Although the focus remains on the propulsion system, the significant advances of other helicopter subsystems should not be ignored.

For the examples shown, fuel consumption was typically reduced by 15% while engine power/weight ratios were increased by an average of nearly 50% as shown in Figure 18.

As a result of increased power/weight ratios, greater reliability, and reduced specific fuel consumption, turbine engine manufacturers have been able to provide a continual increase in performance and operational improvements at lower operating costs to military as well as commercial customers.

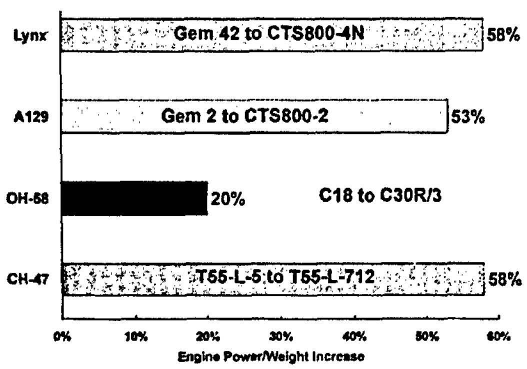


Figure 18. Power/weight ratio affords increased power but not at the expense of payload.

CH-47 Chinook Cargo Helicopter

The Boeing CH-47A Chinook cargo helicopter (Figure 19) entered U.S. Army service in 1962 equipped with two 2,200 shp Lycoming T55-L-5 engines. With a gross weight of 33,000 lb the helicopter was capable of delivering a 6,000 lb load to 100 NM and return without refueling in high hot conditions.

The current AlliedSignal T55-L-712, with a sea level standard takeoff rating of 4,378 shp, installed in the CH-47D, nearly doubles the takeoff power available. As a result when coupled with advanced rotor systems and increased capacity main rotor transmissions the current 'D' version can move nearly 14,000 lb the same distance, an increase of 233%.

Figure 19. Boeing Helicopter CH-47 Chinook.

A future version, dubbed the Improved Cargo Helicopter, with T55-L-714 engines is planned and will further increase the takeoff power of the FADEC controlled engines to 5,700 shp while reducing SFC another 15%. As a result the lift capability will improve to nearly 20,000 lb for the same 100 NM mission.

OH-58 Kiowa

The Bell Helicopter OH-58A entered U.S. Army service in 1969. The 'A' model was powered by a single 317 shp Rolls-Royce Allison C18 turboshaft engine. Designed as a Light Observation Helicopter (LOH), this versatile helicopter could be configured for troop transport, MEDEVAC, and for external lift missions with a cargo hook. However, the temperate conditions of South East Asia seriously limited the capabilities of the helicopter.

With the advent of the OH-58C model, a more powerful 420 shp C20B engine was installed offering a 32% increase in installed power at only an 11% increase in engine-installed weight.

Today, the OH-58D mission has become much more sophisticated and demanding. The transformation to the OH-58D configuration, shown in Figure 20, included a significant list of improvements in addition the 650 shp Rolls-Royce Allison C30R/3 engine with a FADEC.

Figure 20. Bell Helicopter OH-58D Kiowa Warrior.

The original two-bladed teetering rotor was replaced with a sophisticated four-bladed soft-in-plane rotor system that significantly enhanced not only the performance of the helicopter but also its maneuverability. To support the 55% increase in installed power, the entire dynamic system was replaced.

Remarkably, the OH-58 has been continuously improved now for over 30 years with three complete engine upgrades. When compared to the original OH-58, the current OH-58D gross weight has increased by a whopping 90% with a doubling of the installed power.

UH-60 Blackhawk

The Sikorsky UH-60 Blackhawk (Figure 21) utility helicopter entered U.S. Army service in 1976 and represented a significant advance in rotorcraft technology from the UH-1H of the day. In the last 23 years, the UH-60 has benefited from an improved version of the T700. The T700-GE-701C provides an 11% increase in available power for improved hot/high performance.

As a result of the increased power, the lift capability of the UH-60 has increased significantly. For example, the original 'A' model is capable of moving a 4,000 lb load to a distance of 75 kilometers. With the additional power of the -701C engines the payload carried has increased to over 6,000 lb. This represents an increase of 50% simply due to the additional power available.

Figure 21. Sikorsky UH-60L Blackhawk.

AH-64 Apache

The Boeing AH-64 Apache (Figure 22) is the U.S. Army's premier attack helicopter. Having entered service in 1984, the AH-64 has benefited from several upgrade programs to improve the performance of the helicopter and enhance its mission capabilities.

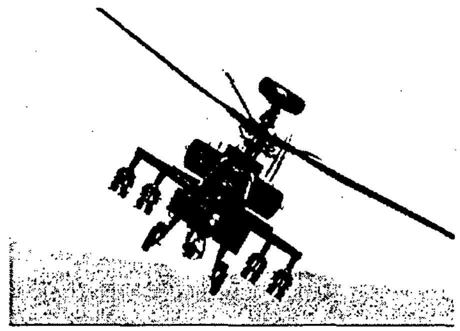


Figure 22. Boeing Helicopters AH-64D Apache.

The WAH-64 Apache will soon enter service with the United Kingdom Army powered by the Rolls-Royce/Turbomeca RTM322 engines. The RTM322 engines provide an 11% installed power increase with only minor changes to the engine bay. In addition to an increase in installed power, the operator will also benefit from its FADEC, efficient integral particle separator, modular construction, lower support costs, and longer life.

Westland Lynx

The GKN Westland Lynx is the premier utility helicopter of the United Kingdom Ministry of Defence (Figure 23). Fitted for Army and Royal Navy duty, the first Lynx's entered service in 1984 powered by Rolls-Royce Gem 42 engines.

Westland is proposing to replace the Gem 42 engines with LHTEC CTS800-4N turboshaft engines in several worldwide markets.

With the CTS800-4N engines, cruise fuel flow is reduced by 15% and available power is increased by 36%, yet the overall propulsion weight is reduced by 24 lb. This is a perfect example of how engine technology enhances mission capability.

Figure 23. GKN Westland Lynx.

Agusta A129I

The Agusta A129 (Figure 24) entered service with the Italian Army in 1990. The Mangusta is equipped with two Rolls-Royce Gem 2 Mk 1004D engines built in Italy by Piaggio under license from Rolls-Royce.

Agusta is currently proposing an 'International' version for several attack helicopter competitions. The cornerstone of this version is the LHTEC CTS800-2 turboshaft engine. The CTS800 engines provide a 36% increase in installed power with a corresponding 15% reduction in fuel flow.

Incorporation of CTS800 engines along with a new five-bladed main rotor has allowed for a 22% increase in gross weight.

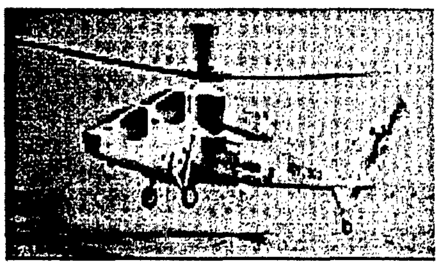


Figure 24. Agusta A129.

V. Future Engine Upgrade Programs

The U.S. Army is currently staffing a draft Operational Requirements Document (ORD) that will push engine technologies to even higher levels. The new requirement proposes an external lift capability of 10,000 lb for the UH-60 Blackhawk and a range of 360 NM. This represents an increase of 66% in lift capability and a 30% increase in range over the current helicopter.

Propulsion alternatives to comply with the ORD could evolve as derivatives of current engines such as the CT7-8 or RTM322 or alternatively, the Army could fund the development of a new centerline engine. If funded and fielded, this engine is expected to provide another 25% reduction in specific fuel consumption, an 80% increase in power/weight, and a 20% reduction in operation and support costs over current technology engines.

Known as the Common Engine Program (CEP), the engine, derivative or new, is expected to power both the Blackhawk and Apache helicopters. As discussed previously, the program will meet both the spirit and intent of Horizontal Technology Insertion.

VI. Conclusions

During the last 40 years, military and commercial helicopter operators have greatly benefited from the advancements in turbine engine technology. Both derivative and new turbine engines have benefited from increases in power/weight ratio, reduced specific fuel consumption operation, and support costs.

Engine upgrades, when teamed with additional rotor and dynamic changes, offer dramatic improvements in overall mission capability as shown in the CH-47D and OH-58D examples. The OH-58D helicopter was transformed from an unarmed, unsophisticated light observation helicopter to an armed reconnaissance helicopter. The ability to make such a large transformation was largely based on improved turbine engines.

As helicopter fleets age and budgets either decline or remain constant and operational demands increase, look to modern turbine engines to leverage helicopter operational effectiveness in a cost effective manner.

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	10 May 1999	Conference Proceedings

4. TITLE AND SUBTITLE

The Modernization of the Snecma military engines: recent developments and prospects

5. FUNDING NUMBERS

F61775-99-WF007

6. AUTHOR(S)

Michel Cockerel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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FRANCE

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES

EOARD
PSC 802 Box 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

CSP 99-5007

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

ABSTRACT (Maximum 200 words)

To date, 47 armed forces have ordered more than 6000 engines sold by Snecma (France) and GE (US). Among the engines that were ordered, some have been in service for more than thirty years. The engines have maintained a high level of satisfaction to the customer. Snecma has an essential program of continuous enhancements covering the life expectancy and reduction in the cost of maintenance.

14. SUBJECT TERMS

EOARD, Snecma, engines

15. NUMBER OF PAGES

N/A

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

La Modernisation des moteurs militaires Snecma
Développements récents et perspectives

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1. Introduction :

A ce jour, 47 forces armées exploitent plus de 6000 moteurs vendus par Snecma ou par CFMI, la filiale commune (50/50) entre Snecma (France) et GE (US). (fig 1)

Parmi ces moteurs en exploitation, certains, ont en service depuis plus de trente ans (fig 2).
De façon à maintenir un haut niveau de satisfaction de la clientèle, Snecma s'impose un programme d'amélioration continue, couvrant notamment :

- Extension des durées de vie et réduction des coûts de maintenance.
- Proposition de modifications dues aux changement d'utilisation.
- Participation de l'industrie des pays-clients.

Les paragraphes suivants montrent l'application de ces principes à différents programmes Snecma.

2. Le programme ATAR

L'ATAR 9C équipe les Mirage 3 et 5. L'ATAR 9K50 équipe le Mirage F1 et le Mirage 50. La base des utilisateurs actuels ATAR (fig3) inclut des clients à ressources limitées et qui souhaitent utiliser les moteurs jusque vers 2020.

Snecma s'est engagée à assurer le soutien de la clientèle jusqu'à la fin de la période d'utilisation des moteurs ATAR.

De façon à ce que cette exploitation se déroule dans des conditions économiques acceptables, Snecma s'appuie sur les outils suivants :

- Des contrats de soutien à long terme avec la clientèle.
- La maintenance modulaire (fig.4)
- L'échange standard de modules de préférence à la réparation
- La disponibilité de pièces de seconde main.

2.1. Snecma a mis en place un Centre de Ressources de matériel ATAR 9C de seconde main (fig.5) – Snecma publie régulièrement une liste de pièces de seconde main disponibles et répond aux appels d'offre client en privilégiant la fourniture de ces pièces, en complétant si besoin est, par des pièces neuves.

De cette façon le prix supporté par la clientèle est optimisé.

Snecma assure aux pièces de seconde main le même niveau de qualité et de garantie que pour les pièces neuves.

2.2. L'ATAR 9K50 (équipant le Mirage F1 et le Mirage 50) fait l'objet d'un programme d'amélioration technique dénommé « ATAR PLUS » lancé en 1995 en coopération entre Snecma (France), ITP (Espagne) et Denel Aviation (Afrique du Sud).

Ce programme inclut :

- Une modification OGV compresseur (fig.6)
- Une modification NGV turbine HP (fig.7)

3. Le programme M53

La base utilisateurs actuels du Mirage 2000, équipé du moteur M53 (fig.8) inclut des clients soucieux de l'optimisation de la maintenance et des performances de leurs matériels.

C'est pourquoi Snecma a procédé à une amélioration de la turbine HP du moteur par l'introduction d'aubes en DS 200 (fig.9 et 10), ayant pour effet :

- Une meilleure résistance mécanique.
- Une amélioration de durée de vie.
- Une amélioration des performances.

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

3. Le programme TYNE

Le moteur TYNE propulse les avions cargo Transall et les patrouilleurs maritimes Atlantique.

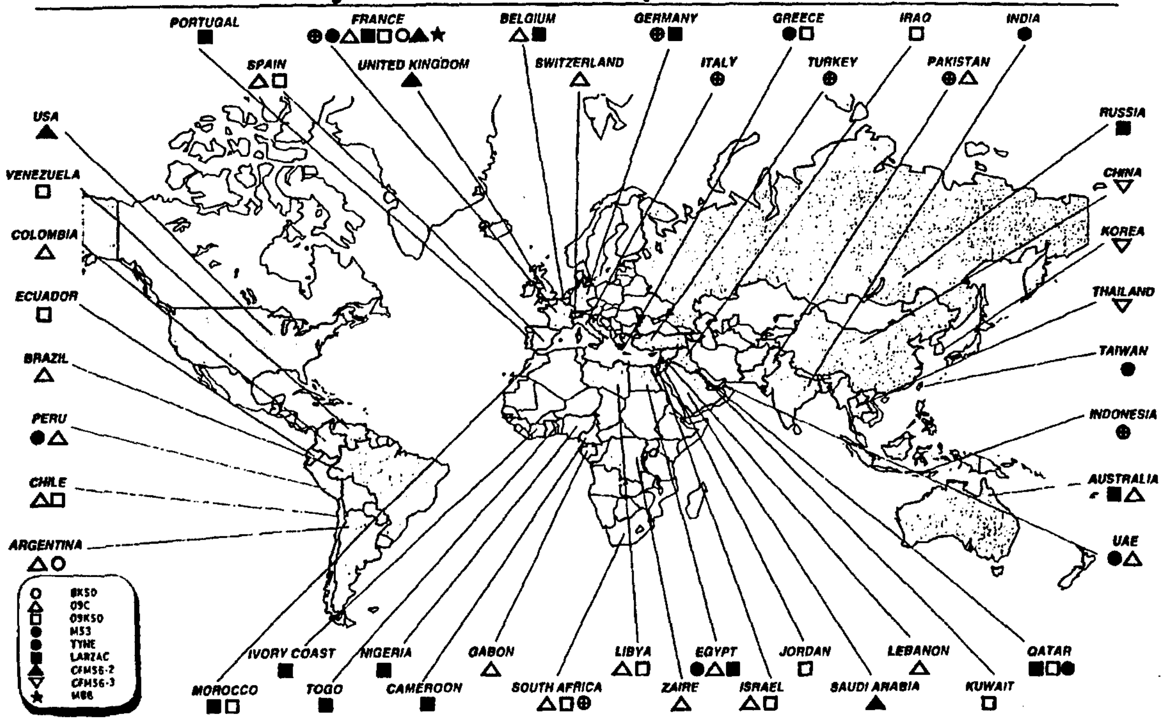
Des améliorations de performance du moteur ont fait l'objet d'études avancées, mais la clientèle a demandé à Snecma de privilégier la réduction du coût de maintenance du moteur dans sa définition actuelle.

Pour cela, un contrat de soutien à long terme a été conclu entre Snecma et le ministère français de la Défense pour le soutien des moteurs Transall (Armée de l'Air) et Atlantique (Marine), dont les principales caractéristiques sont les suivants :

- Durée du contrat, 10 ans.
- Coût sur la base de l'heure de vol.
- MTBO garanti : 750 heures.
- Stock de sous-ensembles « rotables ».
- Snecma gère le stock pièces de rechange.
- Système spécial d'échange d'information centre Snecma et utilisateurs.
- Assistance technique Snecma permanente auprès des utilisateurs.

(fig.1)

Snecma Military Customer & Operator Base



(fig.2)

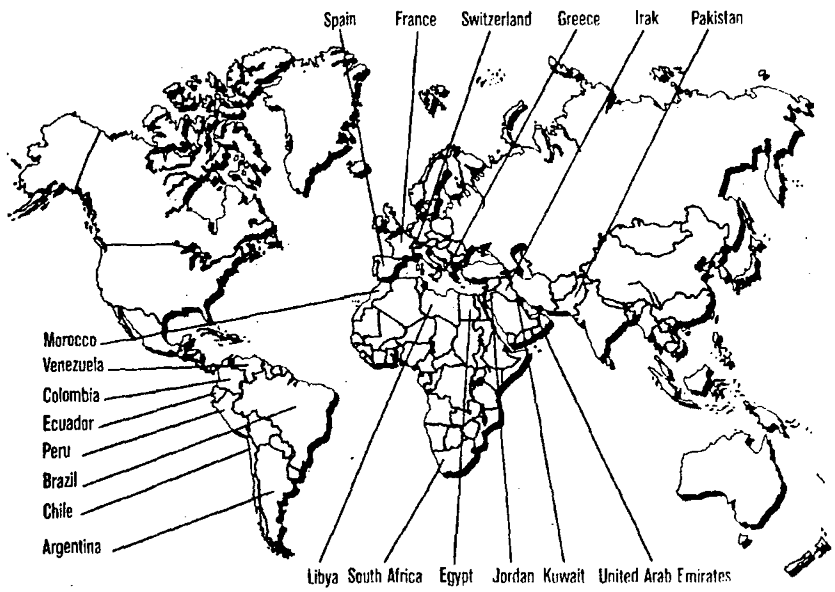
SNECMA Military Engine Experience (as of December 31st, 1998)

ENGINE	AIRCRAFT	ENGINES IN SERVICE	OPERATORS	SERVICE EXPERIENCE
• Atar 8/09K50	Super Etendard, Cheetah, Mirage F1, 50	845	14	1,817,000 h
• Other Atar (8C/9C/9K)	Etendard, Mirage III, IV, V	768	15	4,095,000 h
• Tyne	Transall, Breguet Atlantique	840	9	5,622,000 h
• Larzac	Alpha Jet, Mig-AT	1,133	12	2,753,000 h
• M53	Mirage 2000	626	8	700,000 h
• CFM56-2A/-2B/-2C	E-3, KE-3, E-6, DC8-72 C-135FR, KC-135R	2,000	7	6,890,000 h
• CFM56-3	B.737-300	13	3	78,000 h
TOTAL	20	6,225	48	23,075,000 h

EVERY MINUTE,
A SNECMA MILITARY ENGINE TAKES OFF

(fig.3)

A WIDE ATAR OPERATORS BASE (as of January 1st, 1999)



20 operators - 1,571 engines in service - 6 MEFH

(fig.4)

ATAR 9K50 – Description and Technology

- The ATAR 09K50 is broken down into Overhaulable Sub-Assemblies (OSA) which are interchangeable as far as their dimensions and operation are concerned

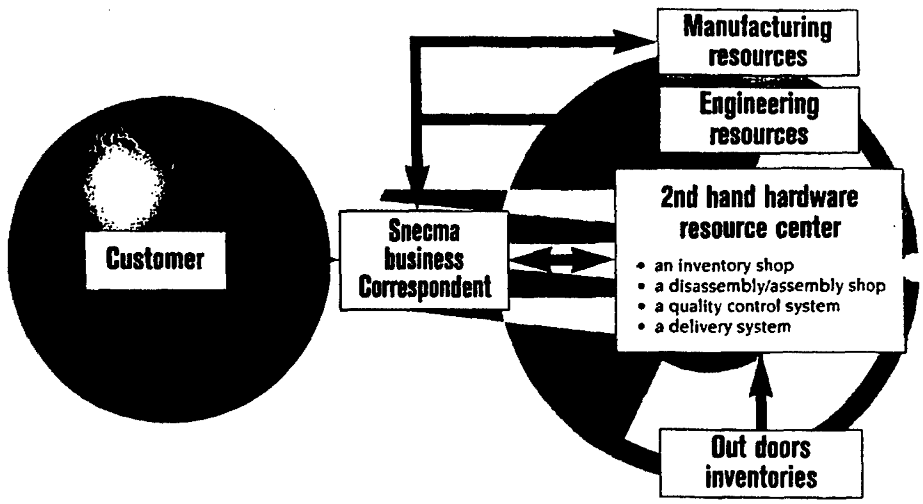
- There are 23 structural sub-assemblies, 4 sub-assemblies for equipment parts and 93 accessories included in the sub-assemblies but which may be replaced individually

Main Sub-Assemblies

MILITARY ENGINE DIVISION ATAR SECOND HAND HARDWARE RESOURCE CENTER

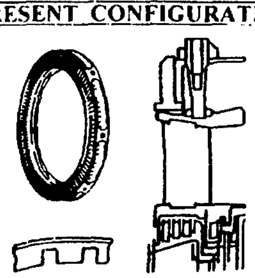
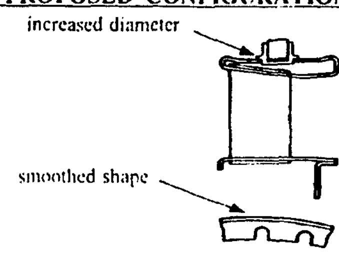
HOW IT WORKS

(fig.5)



COMPRESSOR OGV MODIFICATION

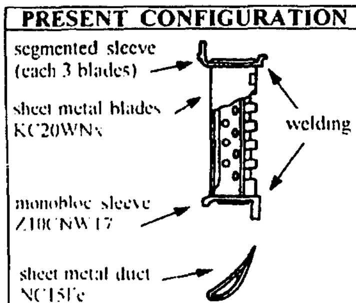
(fig.6)

PRESENT CONFIGURATION		PROPOSED CONFIGURATION
	Definition	
Z6CNT18	Material	NC19FeNb (Inco718)
peened blades (brazing on repair AgCuZnCd630)	Process	blades brazed all along its periphery (NiPdCrB980)

MECHANICAL CHARACTERISTICS IMPROVEMENT

HP TURBINE NGV MODIFICATION

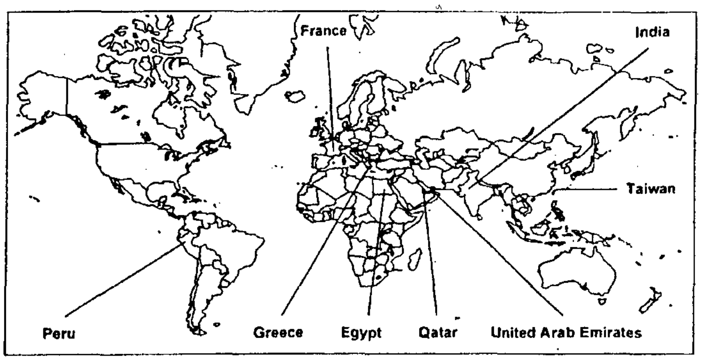
(fig.7)

PRESENT CONFIGURATION		PROPOSED CONFIGURATION
	Definition	
KC20WNx, Z10CNW17, NC15Fe	Material	KC24NWTa
sheet metal, welding, etc	Process	monobloc cast triplets

MECHANICAL CHARACTERISTICS IMPROVEMENT

M53 Customers (as of December 31st, 1998)

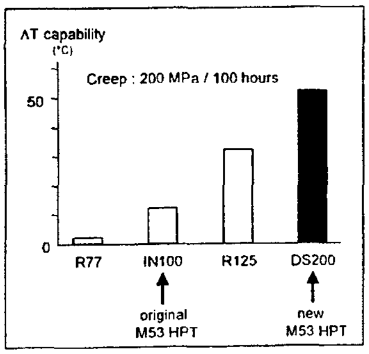
(fig.8)



**626 ENGINES IN SERVICE
IN 8 AIR FORCES**

M53-P2 HPT Blade DS200 Properties

(fig.9)

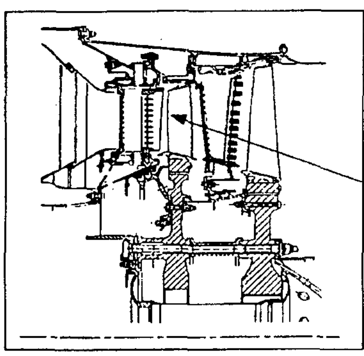


- higher stress rupture
- higher oxidation resistance
- coated with C1A (chromium and aluminium)
- used on Larzac engine since 1985
- (DS200 + C1A) bring twice more life than (IN100 + APVS)
- in production since September 1993

**DS200 HAS DEMONSTRATED
SUPERIOR TEMPERATURE CAPABILITY**

M53-P2 Turbines

(fig.10)



- directionally solidified alloy : DS200
- oxidation and oxysulfuration coating : C1A

**EFFICIENT, RELIABLE
AND COST EFFECTIVE**

LESSONS FROM THE FRONT LINE: THE ROLE OF FLIGHT TEST IN AIRCRAFT UPDATE PROGRAMS

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INTRODUCTION

Many nations today face the choice between procuring new aircraft or upgrading their existing fleet aircraft. An upgrade is frequently seen as a cost-effective solution to meet new mission requirements in a timely fashion. An upgrade allows the user to capitalize on technological advances since the development of the basic airframe. A key aspect of any aircraft program, whether an upgrade or an initial development, is the flight test phase. Flight test is the final stage where the new capabilities are evaluated for their likelihood to deliver added utility to the warfighter. However, given an avionics upgrade for a proven aircraft system, such as the F-16, the need for a flight test program is often questioned. "After all, it is only software" is a common comment. This paper will explore the need for, and benefits of, flight test in upgrade programs. It will address the economics of testing, examine the limitations of upgrades, and touch on issues of incorporating new technology into existing weapon systems. Examples and lessons learned from actual programs either tested or currently under test at the 416th Flight Test Squadron, Edwards AFB, California will be incorporated. These flight test lessons can be easily applied to other procurement programs.

BACKGROUND

The 416th Flight Test Squadron is responsible for over 50 ongoing F-16 test programs. Projects range across the spectrum of testing from a simple field service evaluation of new brakes, to testing a complete avionics modification kit, or entire new aircraft versions. This paper will focus on some lessons learned and as such may give the impression the F-16 is a weapon system infested with software errors, or 'bugs'. Nothing could be further from the truth. These are the experiences resulting from a large volume of flight testing, spanning a large number of customers and subsystems. The upgrades performed have led to the addition of very complex combat capabilities to further expand the F-16's operational capabilities.

I. What can be done economically?

Flight test is expensive, and fiscal realities will force a balance between desired and required testing. Despite advances in modeling and simulation, flight test remains an essential component of any test program. The breadth and depth of testing has a direct impact not only on the cost required to complete testing, but also on the confidence with which the upgraded system can be fielded. Testing of modern, complex systems poses a challenge which leans more toward increased testing depth. At the same time, modern expendable weapons are generally very expensive, making traditional full-scale firing trials a rarity. A live weapon delivery will greatly increase confidence in the system under test if it is performed in an operationally representative scenario. However, such scenarios are often costly and thus must be carefully chosen to get the most value from each test dollar. Specific examples include inertial-aided munitions (IAM) integration and advanced medium range air-to-air missile (AMRAAM) launches. This section will also consider regression testing and adaptation of commercial-off-the-shelf (COTS) systems.

Modern weapons are becoming increasingly complex. Flight test of these weapons becomes an integration effort involving multiple subsystems most often produced by different organizations. For example, an air-to-air missile may require tracking information from the fire control radar which is processed by a central computer to perform its role. The normal flow of evaluation for such a system involves bench testing of each subsystem followed by laboratory testing of the integrated system and finally flight test. Flight test often consists only of captive carry missions but may include a live weapon delivery. The benefit of integration laboratory testing is that it allows a thorough checkout

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

of the aircraft weapon interface. The test team can quickly move through a large matrix of scenarios checking each mode of the interface. The benefit of captive carry testing is that the aircraft and target dynamics are present. An often-unrecognized disadvantage of both laboratory and captive carry testing is that an engineer or computer must verify proper accomplishment of each of potentially hundreds of steps involved in delivering the weapon. Confidence in the results is as much a function of the thoroughness of the engineering analysis as it is the thoroughness of the matrix of test conditions. Live weapon deliveries have the advantage that each of the steps required to operate at the test condition is verified by real world results.

For example, a live delivery of a new weapon at the F-16 Combined Test Force uncovered a problem when a sequenced multiple release, known as a ripple delivery, was performed. A ripple delivery was one of the scenarios tested in the laboratory, but the precise timing of the solenoids, which were energized to remove an arming pin from the weapon, was not verified. During the live delivery, the solenoids for the second weapon did not energize in time to pull the pin that armed the weapon. As a result, the weapon hit the target but did not function correctly. Post-mission laboratory simulations of the event clearly identified the problem. Without a live weapon delivery at this test condition, the problem would have gone unnoticed until the system was fielded. In the case of a high-value weapon which is infrequently delivered in training, the problem may not have been discovered until the weapon was employed in combat.

In another example, an F-16 was upgraded with a new central computer and fire control radar. The software for the new computer and the radar was rewritten in a different computer language starting from the specifications. In this scenario, it is common for the developers to downplay the need for testing because the functionality of the systems have not changed—the software has merely been converted to run on a new system. However, when software is rewritten from the specifications, there are opportunities for errors resulting from mistakes in both designing the code and in interpreting the specifications. A mistake in interpretation of the specification may not be uncovered until the integrated system is tested because the developer will test the system against the misinterpreted specification. If a problem such as this passes bench testing at the vendor and through functional testing in the laboratory, it may manifest itself as a performance problem that will require a realistic, operational scenario to uncover. In our example, latent data were being provided to a radar guided missile, due to an error made in the interpretation of the specification. The problem was not uncovered in contractor bench testing because the system was performing according to its design. The problem was not uncovered during integration laboratory testing because the integration laboratory used targets of opportunity to test the system instead of dedicated target aircraft instrumented to provide precise position truth data. Captive carry flight testing of the system allowed measurement of the data accuracy in a scenario closely related to operational employment. In this example, the problem was only uncovered during the detailed analysis of captive carry flights that preceded a live launch of the missile. At this point, it is useful to note a practical argument in favor of conducting live weapon deliveries. A live weapon delivery actually buys more than just the data from that specific test condition. It is the nature of the compressed timelines associated with today's development programs that engineers must prioritize the time they spend looking at any particular set of data. A live weapon delivery is a milestone in any program and forces the development team to focus its attention on the system to be tested. In the case of the F-16 missile launch, it is certain the problem would not have been uncovered until the weapon system was used in actual combat had a live launch not been scheduled. The data had already been received and undergone an initial review and the latent data were not discovered. Because of this experience, we recommend conducting live weapon deliveries that demonstrate the capabilities of greatest interest to the future system operators. This example also highlights the sophisticated test and range assets frequently required for flight test of complex weapons. Without precise position truth data, this deficiency would likely have been fielded in a production software release.

Many of the upgrade programs tested at the 416th Flight Test Squadron are primarily software modification programs. In order to limit the cost of flight test, less testing is performed on systems which have only slight modifications from a previously tested design. The test team must take care when determining the scope of a particular change. Rehosting software on a newer computer may reasonably be considered a relatively small change. Rewriting software to a more modern computer language like C or ADA should not be considered a small change. Because such software upgrades are commonly performed by producing the code from scratch, based on specifications, the resulting system is actually untested. If the goal is to reproduce the capability of the preceding system, testers may have the benefit of a performance baseline against which to evaluate the new system. It would not be correct; however, to assume that minimal testing is required for the new software code.

Evaluation of previously existing functions to ensure changes to the software did not alter previously existing capabilities is called regression testing. Experience at the 416th Flight Test Squadron shows most upgraded software will contain a few regression errors; typically of small impact, but some of serious consequence. Aircraft software is conceived of and built by humans who occasionally make mistakes. As anyone who has worked in the spectral world of programming knows, these bugs can be difficult to find. To expect any complex software code to work flawlessly the first time would be unrealistic. However, a complete test of a software suite following changes to a few lines of code would be very expensive and not prove any more useful than a carefully selected test matrix of regression points. One method of reducing the scope of regression testing has been to develop modular, stand-alone software codes, sometimes known as 'plug-and-play' modules. The design concept is that software changes or updates will be focused in a specific module, and only that module will require detailed test scrutiny. Problems arising from 'plug-and-play' software updates will be addressed in the technological limitations section later in this paper.

All testing, whether it be laboratory, ground or flight test, is essentially risk-reduction. The cost of executing the test is weighed versus the cost of fielding a flawed system. Without a very large budget, it becomes an art to sift through the plethora of possible test scenarios and build a test plan. It is human nature to build a plan which focuses on new or changed capabilities. A complete test plan must also incorporate an effective way to check for regression errors which are very likely to exist in upgraded software.

Commercial-off-the-shelf (COTS) systems are often presented as requiring less test than systems which were newly designed. This is true in the sense that COTS systems will require less testing at the bench level because they are often well understood at this level. However, because a COTS system was not designed specifically to integrate with a particular aircraft, testing of the interface of the COTS subsystem with the aircraft as a whole must receive more focus. Experience shows two areas where a COTS system may have problems when integrated into an upgraded aircraft. First, a relatively new COTS system may not properly interface with the older architecture of the upgraded aircraft. Second, the COTS system may not have the desired military utility.

The integration of the digital terrain system (DTS) into the F-16 provides a good example of a COTS update program. The DTS was based upon the TERPROM™ system using radar altimeter readings and a stored digital terrain database to determine the aircraft's geographic position. The DTS predicted the aircraft's flight path using current position, velocity and attitude information. The DTS then compared the prediction to the digital terrain database. If a collision with the ground was predicted, DTS generated warning cues to the pilot. Other capabilities, such as obstacle avoidance and a terrain cueing system, similar to a terrain-following system, were also available. The DTS was a self-contained 'black box', with the primary algorithm operating on stand-alone hardware housed in the existing data transfer cartridge.

In Phase 1 of integration, the first task was to link the DTS 'black box' to the F-16's core avionics software. Changes to the core software were necessary because the DTS required information from the radar altimeter and inertial navigation system (INS). The DTS system also provided data to the F-16 core software, used for generating status and warning displays for the pilot. Once the F-16 core was modified, DTS was ready for flight test. Because DTS used a 'generic' fighter performance model with a limited envelope, the initial integration was expected to require some algorithm 'tuning' before fielding for operational use. The anticipated performance tuning and envelope expansion proceeded essentially as forecast. However, when DTS was matched with the F-16's high performance characteristics, unforeseen problems arose with the secondary capabilities of DTS. These problems required extensive analysis and algorithm modification. Additional software refinements were added as the users sought to take advantage of other potential capabilities. In the end, the 'tuning' process evolved into another full integration phase, with two more F-16 core software releases and numerous DTS software changes. The DTS / F-16 integration provides a vivid illustration of how a COTS system required not only significant modification of the F-16's existing core software, but also modifications to the COTS software, and a large flight test effort to produce a system with the desired military utility.

Conceptually the economics of flight testing aircraft upgrade programs are quite simple. The time and money required to conduct a flight test program should be balanced against the potential cost, in dollars and lives, of fielding a flawed system. The preceding examples were intended to provide the reader with some insight into the types of problems which are commonly uncovered in a flight test program. Hopefully this insight will be helpful in determining the appropriate amount of flight test for an aircraft upgrade program. The following section will address three types of limitations frequently discovered in testing an upgraded aircraft.

II. What are the limitations to upgrades?

Limitations, which remain unidentified until the flight test phase, tend to fall into one of three broad categories: technological, programmatic or operational. Unforeseen technological limitations may result from such things as avionics bus architecture, timing and protocol issues, mixing analog and digital systems, or the existent growth capability in the system. Some causes of programmatic limitations are being forced to 'do more with less' or the bureaucratic inertia of multi-user projects. Operational limitations are marked mainly by pilot-vehicle interface (PVI) problems, and unforeseen shortcomings which appear during system employment.

Some technological limits arise from the special requirements of flight test. It is often impossible to monitor system operation without adding flight test instrumentation, which changes, to some degree, the system under test. This problem becomes more significant as the aircraft computer systems are consolidated resulting in fewer black boxes on the aircraft. In one upgrade program, the component which performed weapon ballistic computations and the component which calculated the aircraft height above target were replaced with a single component which performed both of these functions. Before the upgrade, the flight test instrumentation system could record the aircraft calculated height above target as it was communicated from one component to the other via the MIL-STD-1553 avionics multiplex (mux) bus. After the upgrade, the software in the new component was modified to include a "data pump" which put the height above target on the mux bus so the instrumentation system could record it. The 'data pump' was later disabled when the system was fielded. This resulted in a system under test that was different than the fielded system. Flight test instrumentation becomes more and more reliant on 'data pumps' as more and more operations are performed within a single aircraft component. Engineers require data from points within the operations in order to troubleshoot software problems. However, the greater number of 'data pumps' present in the flight test software may lead to greater differences between the system under test and the fielded system. An increase in the differences between the tested system and the fielded system causes a decrease in the confidence in the validity of the test results.

The chief differences between systems with and without a 'data pump' are the timing and quantity of messages transferred via the data bus. In one test program, computer halts and crashes occurred when the 'data pump' was functioning because the multiplex data bus did not have the capacity to handle both the normal data and the flight test 'data pump'. However, when the 'data pump' was disabled to allow production-representative bus traffic, no diagnostic information was available to troubleshoot a performance anomaly. In a new development program, the 'data pump' usually takes up some of the excess capacity of the mux bus. In an upgrade program, this same excess capacity may be required by a new capability. The 'data pump' may have to be modified to provide more types of data while using less data bus capacity. This generally equates to a more complex 'data pump' and thus a less production-representative system under test.

Developers implementing 'plug-and-play' modules can encounter technological limitations if they do not have a thorough understanding of the intended use of their subsystem. A thorough understanding of the integration of multiple subsystems can be hard to attain when multiple organizations are involved in a program, and each organization is striving to reduce the time and money spent developing its individual subsystem. The key component is often the core software, which integrates the different subsystems. As modules are pieced together one or two at a time, the core code and architecture should be capable of handling the load. As the modules become more numerous, ensuring they do not overload processing hardware capabilities or cause timing/interrupt problems becomes more difficult. Unforeseen interactions between the modules can also lead to serious deficiencies.

This exact scenario has been demonstrated several times on various programs at the 416th Flight Test Squadron. Main computer crashes have occurred when system A, which was developed for one customer and system B, which was designed for a second customer were implemented together on an aircraft for a third customer. In another program, computer halts occurred during bombing runs because the developer did not envision the pilot's use of an identification, friend or foe (IFF) airborne interrogator while the aircraft mission computer was configured for bombing. These problems are often the result of hardware resource conflicts and are not uncovered until the system is used in a particular scenario. Resource conflicts become more difficult to avoid as software becomes increasingly complex. Because the programmers and laboratory testers are not fighter pilots, they may build and test the code using false assumptions about system employment. Flight test planners should focus on operationally-representative scenarios in order to ensure the modes needed by the user will work as desired.

In this particular case, an aircraft is much like a personal computer system at work or at home. The major software companies' profits and viability ride on making each application easy to operate and resistant to crashing. Despite the best efforts of the programmers and testers, few people can say their computer has never crashed while performing an apparently routine task. Modern aircraft are more complex than personal computers, and there are many opportunities for problems to be caused by the interaction of the various subsystems. Also, the safety implications for an aircraft's computer crashing far outweigh the safety implications of a home computer crashing.

Another technological limitation observed by the 416th Flight Test Squadron is the difficulty in adapting analog communications systems to transmit digital data. Any system, which utilizes the existing aircraft radios to transmit or receive data, may encounter technological limitations. The radios in most fielded aircraft were not designed for digital data transmission. An upgrade program aimed at adapting these radios for digital data transmission may encounter some difficulty, and the contractor may be unlikely to highlight these limitations beforehand.

The sheer inertia and bureaucracy of large multi-national or multi-service development efforts can result in programmatic limitations to what can be accomplished through an upgrade program. The Link 16 Multifunctional Information Distribution System Low Volume Terminal (MIDS/LVT) and the Joint Direct Attack Munition (JDAM) are examples of multi-user development efforts. Multi-national and multi-service development efforts have the benefit of allowing multiple users to pool their resources to develop a subsystem. However, with multiple users come multiple sets of priorities. Each user has their own operational doctrine and views on how best to employ the upgraded system. 'Joint' programs from more than one service of a single country have enough problems with this. 'Joint' programs involving more than one country can encounter such large programmatic limitations the ultimate result is program cancellation. Making significant changes to a program once it has reached the flight test phase can be extremely difficult.

From the flight test perspective, such programs have the disadvantage of being inflexible. Because each user must approve the subsystem design, it becomes difficult or impractical to change the design when platform-specific deficiencies are uncovered in flight test. From a technical standpoint, the fix to an integration problem might be more appropriately accomplished in the new system, but the inertia of the program may make this impossible. The aircraft developer will be forced to make changes to fix the problem on the aircraft side of the interface. Such unplanned changes will certainly increase costs, could strain avionics system resources, and may decrease the combat capability provided by the upgrade.

Operational limitations occur when a system functions as it was designed, but turns out to be less useful than anticipated. In aircraft upgrade programs, cockpit displays provide many good examples of operational limitations. Most cockpit displays were designed when there was less information available for display. When new information is added to the display by successive upgrade programs, it is possible to overload the pilot with too many symbols. An example might be a horizontal situation display that shows each aircraft in a four-ship formation and the target being tracked by each aircraft. Add navigation routes, geographical borders and radar steerpoints and the display may become so cluttered as to actually decrease the situation awareness of the pilot.

A related problem can be caused when a new system adds to the list of symbols being displayed to the pilot, but the display processor is not upgraded to handle this additional information. In some cases, the display processor has been overwhelmed and 'locked up', thus causing a complete loss of situation awareness instead of just possibly a degraded state of awareness by the pilot. This anomaly requires the pilot to perform some type of 'head-down' operation to restore correct operation of the displays.

Problems will be uncovered during the flight test phase of any upgrade program. A clear, well thought out 'feedback loop' needs to exist to incorporate the findings from flight test into the production tape. This process needs to be well defined in the early stages of any program and not wait until the first 'show stopper' anomaly has been encountered. It is essential to incorporate the most refinements into the production version of the upgrade. These problems are more likely to remain in the fielded system and become limitations if the upgrade program was planned with very little margin for error in a technological, programmatic or operational sense.

III. How can technological advances be integrated?

The underlying theme in today's technological advances is complexity. As operational requirements for weapon systems grow, so does the complexity of the integration. Precision weapons are inherently more complex; that's what makes them 'smart'. The complexity of these systems makes performance analysis difficult for both developers and testers alike. With older, less intensive avionics suites, system performance was usually readily apparent to the pilot. Scoring no hits on an aerial target, with a stable tracking solution on the target, was a straightforward indicator of a gun sight computation problem. Likewise, stray bombs could highlight a bombing deficiency. Today, the weapons themselves communicate with the aircraft via the avionics data bus, and it is prudent to evaluate the communications for all weapon modes, using the most economic testing methods available. This might be analogous to evaluating the internal communications between a computer's CPU and a floppy disk drive. Clearly, the typical computer user would have extreme difficulty evaluating the 1's and 0's passing between the core software (CPU) and the subsystem (floppy drive). This example is useful in illustrating not only the depth of testing required, but also the breadth. Imagine the effort required in testing the computer with a wide variety of applications that might use the floppy drive.

With increases in effective weapon range and system complexity, the question of how to evaluate such weapons without an actual launch or delivery has become more important. The displays to the pilot may or may not be linked to actual system performance. Models used by the avionics computers, such as launch zone and time of flight computations, may have areas of inaccuracy. Even worse, the models may be engineering approximations coded into the software before the actual weapon performance characteristics had been determined. This is increasingly becoming the case as weapons development timelines continue to lengthen. Concurrent development on the aircraft side of the weapon interface is used to shorten the overall development cycle. Using approximations throughout the integration effort can have significant drawbacks, and possibly result in significant problems being found very late in the development cycle.

A careful distinction must be made between using flight test results to verify a model, and using a model to verify flight test results. In one example at the CTF, the proper operation of an existing ground recovery algorithm was regression tested by a number of programs. The aircraft's flight parameters were entered into the 'known' algorithm to verify if the pilot warnings were displayed when the model predicted they would be. The model was used as a truth source because it had been extensively evaluated years before. Unfortunately, an error had been introduced during a minor algorithm refinement. When an experienced engineer used flight test results to verify the model, the flaw was found. Subsequent ground-based testing allowed economical identification of the erroneous portions of the algorithm for correction.

Summary

Aircraft upgrades can be an economical alternative to new aircraft purchases. The key is careful overall program management from the beginning. Any upgrade project must include a realistic testing phase, including flight tests where appropriate. The cost of flight testing a particular feature must be carefully weighed against the risk of fielding a system or component that might not be operationally useful. Although a COTS system should not require very much component testing, it will require a fair amount of integration testing with the host vehicle. The test phase must be allocated enough resources to handle any technical, programmatic, or operational limitations encountered during testing. With the complexity of today's aircraft upgrades, it is unrealistic to expect to have no errors in the first iteration. System complexity may also drive a need for increased test range support capabilities, engineering analysis costs, and possibly expensive live weapon deliveries. A well thought out process to feed the results and refinements from flight test back into the production tape must be established in the early phases of a program. Care must be taken when integrating technological advances into an upgrade program. Concurrent development on both sides of the aircraft interface is usually required and drives the need for using models and approximations in the early phases of design. However, models and simulations should never be used to verify flight test results. Properly handled aircraft upgrades can achieve a significant increase in combat capabilities in a shorter time span and for fewer resources than a brand new development program. The development history of the F-16, from a daytime dogfighter to today's multi-role, precision-strike weapon system, provides ample proof.

The AH-64D Apache Longbow, Affordable Evolution

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The U.S. Army and Boeing Rotorcraft are enhancing the capabilities that made the AH-64A Apache the best attack helicopter in the world. These enhancements are resulting in the most capable, fully integrated, combat weapons platform for the twenty-first century: the AH-64D Apache Longbow.

The Apache was the result of the requirement for an advanced attack helicopter. In the early 1970s, the U.S. Army decided to replace its AH-1 Cobra fleet based on lessons learned from its history (Vietnam), and an analysis of its primary threat, the former Warsaw Pact. The Army's concept was to use "massed forces for massed effects."

New technologies enabling standoff weapons employment; the ability to perform multiple target engagements; and night operations capabilities were combined with redundant systems; ballistically tolerant components; and a crashworthy airframe and cockpit resulting in the AH-64A.

The AH-64A entered service in 1986 with the U.S. Army and later with five international defense forces (Israel, Egypt, Saudi Arabia, the United Arab Emirates, and Greece).

In the Army's endeavor to field a twenty-first century platform, the AH-64A Apache provides the basic airframe; and all the basic survivability features that make it a great, survivable aircraft are retained.

Boeing is digitizing the combat proven AH-64A Apache. Using "state-of-the-art" technology, the AH-64D now merges sensor inputs; generates mission data; generates graphical displays (a picture is worth a thousand words); and manages a wealth of information resulting in a totally integrated weapons platform.

At a glance, the crew has a graphical picture of the battlefield. In the AH-64D, the weapon processors are cooperative and redundant. They share information continuously so that if one fails, the other automatically picks up the load. The Enhanced Global Positioning System Integration (EGI) is also cooperative and redundant and the Inertial Navigation Unit (INU) functions as the primary navigation unit. It is updated two times a second by Global Positioning System (GPS) satellites and receiving Doppler rate sensor input to provide better weapons firing solutions. If the satellites are shut down, it still navigates. The AH-64D experiences three-meter (3m) accuracy virtually every place it operates. That is not as important for navigation of the aircraft, as it is for the collection and digital dissemination of tactical information with other AH-64Ds and compatible aircraft (AWACS, JSTARS) or ground station(s).

The AH-64D is equipped with four (4) on-board radios: two (2) Single Channel Ground-Air Radio System (SINCGARS); one (1) Ultra High Frequency (UHF) Have Quick II; and one (1) Very High Frequency (VHF) Amplitude Modulating – Frequency Modulating (AM - FM). All are capable of secure voice transmissions. The SINCGARS and Have Quick radios possess a frequency hopping (anti-jam) capability. The aircrew can communicate by voice or digitally, in the clear; ciphered; or frequency hopping on any radio.

A Fire Control Radar (FCR) is mounted above the rotor. It is a low power, narrow beam, and frequency agile, low probability of intercept millimeter wave radar. It automatically detects, classifies, and prioritizes targets in five (5) symbol sets: wheel vehicle; track vehicle; air defense; helicopter; and fixed wing. A small number of unknowns can also be placed on the screen. If it is a close-in target, it may also be targeted for destruction. Each of the symbols displayed to the crew is supported by a wealth of information: latitude; longitude; UTM grid; altitude of the target; target classification; and target track information. The crew can display 128 targets and have all of those 128 targets backed up with all of the data described. The FCR prioritizes these targets automatically for the crew. The aircraft has a number of prioritization schemes. The crew can also change those priorities anytime during the flight. The prioritization is very basic: either predator or prey. If it is predator, then it is destroyed first. If it is prey, it is destroyed after all predators. The system considers day, night, moving, stationary, range to the target, and target classification. Air defense is the most dangerous and emitting air defense is even more dangerous.

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

A Radar Frequency Interferometer (RFI) is an array of small passive antennas mounted underneath the FCR, above the rotor system. The array functions very effectively as a radar warning system, providing 360 degrees of coverage.

The Target Acquisition and Designation Sight (TADS) is the primary visual sensor used by the copilot gunner (CPG) in the front seat. It is also the backup night pilotage sensor. The TADS contains Forward Looking Infrared (FLIR) and Day Television (DTV) sensors; a Laser Range Finder (LRF); and Laser Spot Tracker (LST). The spot tracker has the ability to acquire laser energy from any other tri-service compatible designator.

The Pilot Night Vision Sensor (PNVS) is the primary night pilotage sensor for the pilot in the back seat. It is mounted above the TADS on the nose of the aircraft; and operates in the infrared (IR) spectrum.

The Integrated Helmet and Display Sighting System (IHADSS) ¾" television screen attached to the helmet in front of the pilot's right eye is the primary display for the PNVS and aiming reticle for weapons. The sensors and the weapon systems are linked through the integrated weapon processors, which ensures the sights are looking the same place the crew is looking. The radar can detect a target and very rapidly cue any of the weapon sub-systems: air-to-air missile; HELLFIRE missiles; 70 mm rockets; the 30mm chain gun, or in this case, the TADS. All sensor and weapon sub-systems can be linked.

The AH-64D crew stations are nearly identical, the exception being the Optical Relay Tube (ORT) in the CPG station. There is a Data Entry Keyboard (DEK) located on the left side of each crew station, designed so that it can be easily utilized with the left hand during any mode of flight. Data can also be automatically input using a data transfer cartridge, programmed in the operations center using a Mission Planning Station, and carried to the aircraft and inserted in a data transfer receptacle in the pilot's station.

The aircraft is designed to increase crew effectiveness. Fully digitized crew stations enable "management by exception," transferring work from the crew to the aircraft. The aircraft also gives the aircrew superb capability for battlefield coordination. The crew can precisely divide the battlefield to control team fires, similar to the way you would do so with a mouse on your computer. The crew can also identify friendly locations in the same manner it identified priority fire zone box locations. A "no fire zone" inhibits the weapon system from targeting anything within that box. Like every other system on the aircraft, the crew has the ability to re-enter the loop at any time. If a pilot sees an enemy in the no fire zone, he can, in fact, target and destroy him.

The weapons delivery capability of the AH-64D implies a well-armed force suited for any contingency on the modern battlefield, in reduced visibility, day or night.

The AH-64D air-to-ground, anti-armor missile system is the HELLFIRE. It is the primary weapon for the destruction of tanks and other hardened point targets. With four launchers installed, the AH-64D can accommodate up to 16 HELLFIRE missiles in any mix of types. A MIL-STD 1760 launcher has been developed for the AH-64D permitting operation of all HELLFIRE missile models from a single launcher. The HELLFIRE missile system is resistant to active and passive countermeasures. Crew station controls allow the aircrew to enable the counter-countermeasures and minimize the impact of battlefield obscuration.

The Aerial Rocket System complements other AH-64D weapons in providing the capability to fire rockets while on the ground or in the air, at speeds from hover to maximum level flight speed. The AH-64D accommodates up to four lightweight rocket launchers with a total payload of seventy-six (76) Hydra 70 FFARs. The Hydra 70 FFAR is a powered 70mm semi-ballistic projectile with no guidance other than its initial trajectory path. In addition, remote set fuzing capability is incorporated and accommodates use of both penetration and proximity fuze types. A Multi-Purpose Sub-Munition warhead permits use of a "wall in space" technique to achieve highly controlled dispersion and increased sub-munition effectiveness. The wall in space concept is achieved through the use of air burst fuzing and high drag sub-munitions which alleviates sensitivities to variations in pitch angle. A flechette warhead allows effective engagement of exposed personnel and unarmored vehicles and, to a limited extent, airborne targets

The M230 30mm automatic gun is a single barrel, externally powered, chain driven weapon system firing electrically primed ammunition at a rate of 625 RPM. The gun is mounted in a flexible turret located on the forward underside of the fuselage. Its hydraulically driven turret is capable of slewing 11^0 up, 60^0 down, and 110^0 left or right of the armament datum line. The gun's ammunition handling system stores approximately 1,200 rounds of 30mm linkless ammunition and delivers it to the gun on demand. It is used to neutralize or destroy light armor vehicles and other light material targets. It provides an inherent self-defense capability against unanticipated encounters with either ground or airborne targets.

The Air-To-Air-Missile system is designed to ensure an effective self-defense air-to-air missile capability is always available without impacting the ordnance load on the primary weapons platforms. The system accommodates up to four ATAMs carried in pairs and installed on the ATAM airborne launchers at each wing tip station. The ATAM system can be employed by either crewmember independently or in a cooperative, precision mode. The AH-64D accommodates all Stinger ATAM variants in current or planned use.

The U.S. Army plans to employ the AH-64D in its inventory until approximately 2025. With this goal in mind, Boeing and the U.S. Army are working on a cooperative program that will improve AH-64D durability range and endurance while reducing system operating and support (O&S) costs.

Drive Train 2000 (DT2K) will incorporate five (5) major enhancements to the current AH-64D: an advanced main rotor system; a re-engineered center fuselage; a new transmission; a new drive system; and new engines.

Through the use of five composite blades and advanced aerodynamic design that includes the use of elastomeric bearings for blade motion and retention, the advanced main rotor system will achieve lower vibration levels and improve performance.

An integrated design and manufacturing approach using enhanced modeling and simulation tools will shorten design and build cycle times, reduce structural weight, and improve the structural integrity of the AH-64D.

A new transmission and compatible nose gearboxes, clutches, shafting, and lubrication will increase horsepower capability. This increased horsepower capability will enable incorporation of new 3000hp engines currently under development.

In summary, the AH-64D is designed for growth; and is being improved based upon cost affordable evolution. With over, one (1) million hours of service, it is the world's only 4th Generation attack helicopter, proven in combat, and proven in peacekeeping. It's lethal information dominance will keep the world's premier attack helicopter viable well into the third decade of the 21st Century.

MH-53J SERVICE LIFE EXTENSION PROGRAM, A SPECIAL OPERATIONAL FORCES ROTORCRAFT WINNER

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ABSTRACT

This paper presents a summary of the airvehicle modifications (largely structural) that were made and the airworthiness qualification flight test program that was conducted to expand the operational gross weight capability and enhance the structural integrity of the subject helicopter. The impact on both vibration and dynamic component retirement times are discussed. The paper includes both technical and cost information to support program benefits of this modernization approach, *but will address only the basic airvehicle, including its rotor/drive and propulsion systems.* Discussion of special mission equipment peculiar to the special operational forces mission and most shipboard operations features, can not be included.

BACKGROUND

To support the United States capability to conduct Special Operations, the Congress of the United States authorized a comprehensive Special Operations Force (SOF) enhancement program. Legislation further directed that DoD reorganize command structure by creating a Unified Command for Special Operations (USSOCOM). Within the DoD budget, a separate Major Program Force Category, known as Program 11, was established for all SOF budgeting activity. Under these procedures the Service Departments continued to execute SOF programs for USSOCOM using Program 11 funds. This applied to major systems acquisition programs and modernization efforts such as the USAF H-53 variants.

A key congressional concern in examining the DoD's ability to execute special operations has been the status of SOF aviation capabilities. In 1987, the Joint Special Operations Agency (JSOA) provided a SOF Aviation Requirements List to the Congress outlining the enhancements necessary to meet war-plan requirements.

To meet wartime/contingency planning needs, one of these enhanced requirements was the H-53 PAVE LOW weapon system, with the development of an Emergency War Planning (EWP) capability.

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

When combined with the accomplishment of a Service Life Extension Program, and a Shipboard Operation Program (SLEP/SBO), an increase in the EWP gross weight (GW) from 42,000 to 50,000 lbs was required to provide a capable air vehicle beyond the year 2000 to meet the demanding combination of payload and fuel for SOF contingency and wartime taskings. Combat search and rescue (CSAR) operational requirements were also addressed, to meet the future DoD long range helicopter needs. An important result of the PAVE LOW EWP capability is the ability to self-deploy to extreme ranges at max GW which allows for a limited number of weapon systems to be strategically based. Tactical missions with flight times in excess of 10 hrs are sometimes required.

The Department of the Air Force issued, several Program Management Directives (PMDs) for Class V Modifications to upgrade the MH-53J with Phase II Special Operations Forces (SOF) improvements. This modification was to upgrade the 41 Air Force H-53's to the MH-53J (SLEP/SBO) with shipboard compatibility and was intended to increase contingency and wartime max operating GW with a congressionally directed completion date of the end of FY90. Specifically, it required: "Design and engineer the increase in maximum H-53 gross operating weight from 42,000 to 50,000 lbs primarily for contingency and wartime operations similar to the C-130 and C-141 emergency war planning (EWP) capability".

In compliance with the PMDs, extensive airframe modifications were accomplished at the former Pensacola Naval Aviation Depot.

ORIGINAL CH-53A CONFIGURATION

The original CH-53A was designed primarily for the movement of cargo, equipment, and troops. It features a single lifting rotor, with an anti-torque tail rotor, and twin turboshaft engines. The fuselage consists of a molded fiberglass pilot's compartment with an electronics compartment beneath. This is attached to the all-metal semi-monocoque cabin section structure, transition section, and tail pylon. Sponsons on either side of the fuselage contain fuel cells and house the retractable main landing gear. The main rotor pylon atop the cabin section houses the main transmission, its oil cooler, and the APU. The turbine engines are mounted in nacelles on each side of the aircraft, and drive the transmission through engine nose gearboxes and shafting. Each engine had an inlet particle separator for sand and dust protection, but without infrared suppression. A horizontal stabilizer is mounted on the upper right side of the tail pylon. The intermediate gear box is installed in the lower portion of the pylon with a shaft extending upward to the tail rotor gearbox at the top of the pylon.

Entrance into the aircraft is accomplished through a door at the forward end of the cabin on the starboard side. A two-piece ramp, with an upper and lower door configuration (power actuated) at the aft end of the cabin (transition section) facilitates ease of cargo handling in conjunction with a self-contained cargo winch system.

The CH-53A was originally designed using a GW of 33,500 lbs and a structural design load factor of 3.0 g's. The maximum allowable GW has increased to 42,000 lbs with an appropriate load factor reduction. Additional mission requirements mandate that the structural integrity of the airframe had to be upgraded for even higher operating weights.

H-53 MODEL EVOLUTION

Since the original CH-53A, several successors have been used by the USAF, including the HH-53B, HH-53C, CH-53C, HH-53H, and now the MH-53J (SLEP/SBO). Many other variants have been/are operated by the US Navy & Marine Corp.

The HH-53B, equipped with T64-GE-3 engines, was basically a CH-53A modified for the USAF combat aircrew recovery (CAR) mission. Changes included an in-flight pressure refueling system using a retractable probe, auxiliary droppable fuel tanks mounted outboard of each sponson, a hydraulically powered rescue hoist above the cabin personnel door, along with armament and armor protection.

The HH-53C upgraded the HH-53B by using T64-GE-7 engines. A cantilevered support for the external auxiliary fuel tanks was used. It also had several advanced avionics systems.

The HH-53H, a.k.a. the PAVE LOW III, enabled the H-53 to perform search and rescue (SAR) missions under total darkness and/or adverse weather. All were retrofitted with T64-GE-7A engines. The structurally significant changes from the HH-53B/C's include a nose modification to support new mission equipment and provisions for two 650 gal (in lieu of 450 gal) auxiliary tanks.

The latest variant, the MH-53J, a.k.a. the MH-53J (SLEP/SBO) and is the basis for this paper. This configuration incorporates numerous structural modifications including improved main rotor blades and a more reliable main rotor head along with upgraded engines. Substantial changes in the mission equipment package (MEP) were made, allowing for safer, more effective means to navigate at low altitudes in total darkness and/or adverse weather over all types of topography, including mountainous terrain.

Details of the mission equipment package (MEP) upgrade with its integrated electronic warfare capability are not presented in this paper, but key airvehicle elements of the MH-53J Service Life Extension Program (SLEP) and shipboard operations (SBO) features are:

- ✓ *IMPROVED MAIN ROTOR BLADES (IRB) (airfoil change, NACA 0011 to SC 1095; blade chord increased, 2.167 to 2.417 ft.; & blade twist increased, –6° to –10. 67°),*
- ✓ *ELASTOMERIC MAIN ROTOR HEAD (ERH) ASSEMBLY with AUTO BLADE FOLD for SBO,*
- ✓ *T64-GE-100 ENGINES,*
- ✓ *INCREASED STRENGTH ACCESSORY GEARBOX SUPPORT STRUCTURE,*
- ✓ *AUTO TAIL PYLON FOLD SYSTEM for SBO,*
- ✓ *RH-53D MAIN / NOSE LANDING GEAR and MODIFIED LANDING GEAR BACK-UP STRUCTURE.*
- ✓ *STRONGER ALLOY TAIL PYLON SKINS without CHEMICAL MILLING,*
- ✓ *STRUCTURAL ENHANCEMENTS in AFT FUSELAGE and TAIL PYLON AREAS,*
- ✓ *STRONGER FUSELAGE UPPER/SIDE SKINS, WITH INCREASED THICKNESS,*
- ✓ *IMPROVED / REPLACED AIRCRAFT ELECTRICAL WIRING SYSTEM,*
- ✓ *NEW AIRCRAFT HYDRAULIC TUBING,*
- ✓ *EXHAUST COOLER, for AUX POWER PLANT*
- ✓ *COLLECTIVE DAMPER.*

In addition to these modifications and additional external mission equipment (altering the aerodynamic profile), an increase in the collective rigging (+ 1.6 degs) was also incorporated.

Side view and plan form view drawings of the MH-53J (SLEP/SBO) are in Figure 1. More detail concerning selected structural modifications follow.

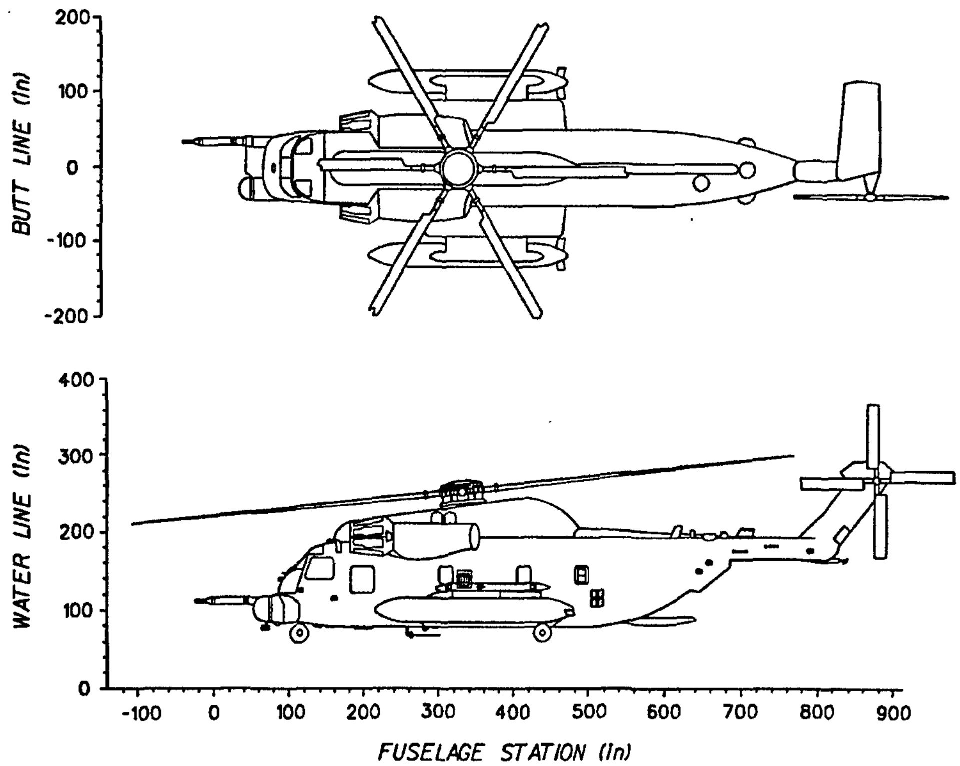


Figure 1. MH-53J (SLEP/SBO) Side View and Plan Form with Coordinate System.

STRUCTURAL MODIFICAITONS

Two major areas of structure modifications will be described here. The design efforts were performed by the Georgia Tech Research Institute (GTRI) with assistance of its subcontractor, the Sikorsky Aircraft Corp for the WR-ALC.

The RH-53D landing gear was purchased "off the shelf", thus requiring new airframe landing gear support structure. The effects of the mission loadings (mass distribution) changes and new max GW were both analyzed. Mass properties were redefined and used by Sikorsky, in generating new flight and ground loads (fuselage shears, moments, & torsions). A finite element model (FEM) was utilized to determine internal loads in individual airframe members.

There were a total of 34 areas with negative margins of safety (MS) in the landing gear support structure.

Cost avoidance issues associated with various design approaches were very sensitive. One of the design goals was to minimize the amount of structural modification while restoring positive margins of safety, without jigging the airframe. Avoiding any type of maintenance requirement to further increase support cost was paramount. The design modifications and their analytical justifications were documented and a proof kit installation was made at the former Pensacola NADEP, followed by all fleet aircraft. Figure 2 illustrates the magnitude of these strength enhancements. Their unit recurring cost was approximately $85,000.

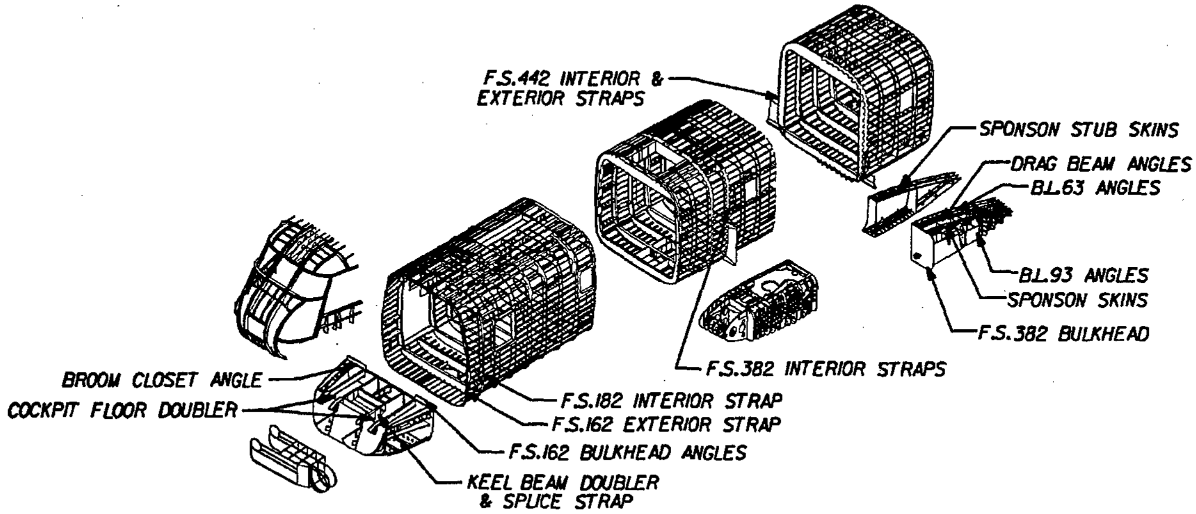


Figure 2. Landing Gear Support Structure Modifications.

Well before the establishment of a formal SLEP, Sikorsky had designed and improved the upper left pylon fold hinge (pylon side); because numerous cracks had occurred in a number of aircraft of all using services, both US and foreign. Many H-53's had other distressed areas in the aft fuselage and pylon area which prompted the WR-ALC to more thoroughly investigate this area during SLEP.

Specific distress areas bubbled up as a result of the Kuwait liberation (Operations Desert Shield/Desert Storm). Twelve MH-53J's experienced structural problems. These aircraft ranged in life from just over 5,000 hrs to 7,300 flt hrs, with an average of approximately 6,200 flt hrs, indicating simply a long term fatigue problem.

This resulted in fatigue strength enhancements designed by GTRI, which included beef-ups of the aft fuselage left upper fitting tang and tail pylon left upper fitting forward arm. A material change in the left upper aft fuselage longeron from 2020-T6 aluminum to quarter hard 301 stainless steel. A left upper longeron strap (fuselage side) and circumferential strap was added at FS 689.5. Pending modifications include a tail pylon left upper fitting aft flange beef-up and a beef-up at the control rod cutout in FS 776 bulkhead. The general area of these structural enhancements is illustrated in Figure 3. The unit modification kit cost was approx. $15,000.

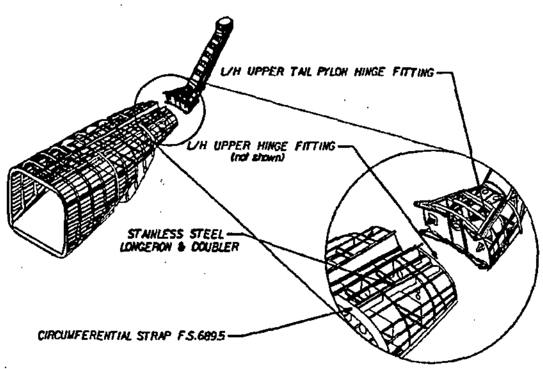


Figure 3. Aft Fuselage / Tail Pylon.

Many other structural enhancements using improved components developed by Sikorsky for Navy H-53 variants were obviously part of SLEP but not discussed here. Firms assisting the WR-ALC in these areas included SRL and E-Systems (Serv Air) in the US and the Israeli Aircraft Industry.

FLIGHT TEST PROGRAM SCOPE

This test program was an essential element of the Airworthiness Qualification process for the MH-53J (SLEP/SBO). It was designated a Limited QT&E Program in accordance with AFM 80-5. It is a.k.a. the Structural Modification Flight Test (SMFT) in USAF documents. Its purpose was to obtain test data to qualify the aircraft for operations at GW ≤ 50,000 lbs and resubstantiate all component retirement times. Its cost was approximately $14M; excluding government in-house expenses, spanning 20 flying mos.

Specific test tasks and the approximate productive flight hour of testing accomplished are in the table below:

• SHAKEDOWN and COLLECTIVE OPTIMIZATION	40 hrs
• AFCS EVALUATION	20
• FLIGHT PERFORMANCE	50
HIGH ELEVATION EVALUATION	13
• FLIGHT STRAIN SURVEY	60
TAIL ROTOR STRAIN SURVEY	7
IN-FLIGHT REFUELING	4
MISSION MANEUVER	3
SLOPE LANDINGS	2
• AFCS VERT GYRO VIB SURVEY	7
• AUTOROTATIONAL FLARE EVAL	5
• SIMULATOR VALIDATION and FLYING QUALITIES	15
	226 hrs

It also provides revised Flight Manual performance charts, and inputs regarding flying qualities and other operational limitations. Operational capability of the helicopter was enhanced by optimizing the maximum collective control available to utilize full T-64-GE-100 power, up to helicopter transmission limits.

Paper page limitations do not permit discussion of all facets of these tests; only a few items of special interest are included.

COLLECTIVE OPTIMIZATION

The first critical issue was increasing the collective up stop to permit full use of available engine power when operating below transmission limits. Figure 4 illustrates the loss in available power for the original (all previous models) collective rigging.

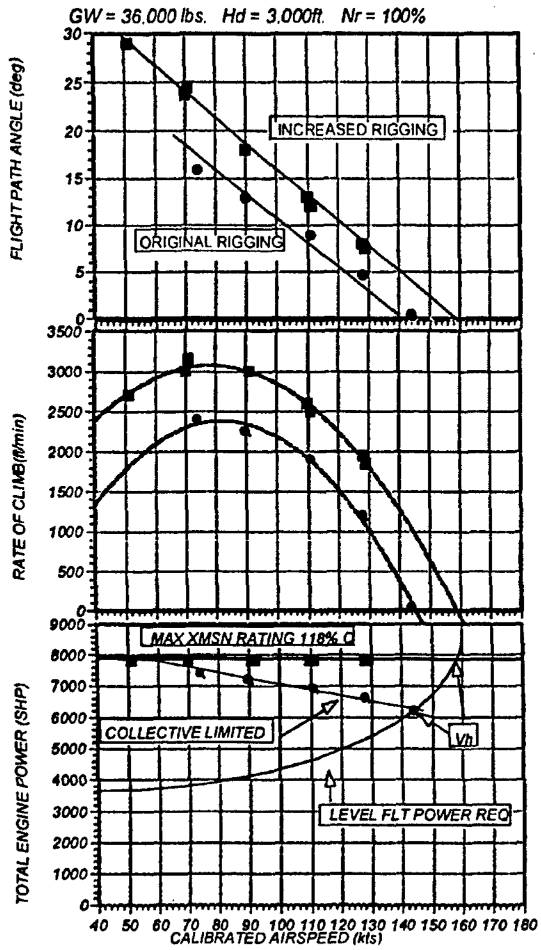


Figure 4. Effect of Collective Up-Rig Setting.

The increase in rate of climb and its impact on flight path angle which enhances Terrain Following/Terrain Avoidance (TF/TA) performance from this additional engine power are clear. This is based on a collective up-rig of 1.6°, which could also increase max airspeeds.

Not all aspects of this rigging increase were beneficial. Rotor downwash during operation on the ground is necessarily increased but reducing the ground operation rotor speed (Nr) from 100% to 95% can minimize its impact. In addition, clearances between the main rotor blades and the airframe are reduced during blade/pylon fold operations. This folding is critical to shipboard operation with over the deck wind. These reduced clearances will require careful monitoring during the folding process.

The increase in maximum up collective has an associated decrease in the maximum down collective due to the fixed actuator length. This naturally impacts rotor speed control during autorotation. While the rates of descent are decreased, obviously desirable, the maximum rotor speed with full down collective is also reduced. Thus, very light GWs fall below the previous 90% min N_r. This can occur only at density altitudes less than 4,000 ft at near the minimum aircraft flying weight.

Because the increased safety associated with improved agility during TF/TA flight is of substantial importance for SOF missions, and the probability of a dual engine failure at very lightweight is so remote, *the advantages of increased collective rigging far outweighed its disadvantages.*

HIGH ELEVATION IGE TESTING

Both civil and military aircraft are routinely tested in-ground-effect (IGE) at one of three mountain test sites. These are Leadville, CO (9927 ft. AGL), Coyote Flats, CA (9980 ft. AGL) and Alamosa, CO (7536 ft.). Because the MH-53J (SLEP/SBO) critical altitude is approximately 7,000 to 8,000 feet, the Colorado test site was selected.

Hover performance was accomplished using the tethered hover technique, because it offers precise height control during IGE work and allows for a wide variation in power. The helicopter is hovered at light GW connected to a "dead man" through a cable containing a load cell. Both engine power and N_r were varied for non-dimensional parameters in terms of weight and power coefficients.

A most important area of high elevation testing is determining the adequacy of tail rotor effectiveness in sideward/rearward flight. This is comparable to hovering in windy conditions. These tests are run using a pace vehicle to track airspeed on an open runway under near zero wind conditions. Tail rotor effectiveness is a function of density altitude, which at the Alamosa Airport ranged from 8,000 to 9,500 ft. on actual test days. Sideward flight measurements of tail rotor control remaining were made at several GW and together with similar data measured at the Sikorsky Developmental Flight Center, West Palm Beach, FL (near sea level elevation) were consolidated into the overall low speed performance capability shown in Figure 5.

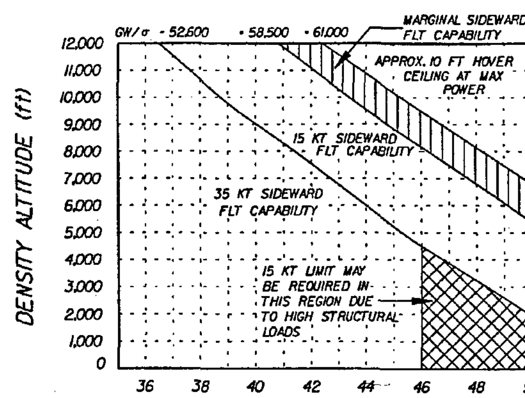


Figure 5. Low Speed Performance Capability.

AUTOROTATIONAL FLARE EVAL

All helicopters have significant reductions in their power-off glide capability with increasing GW and density altitude. Since the MH-53J has increased in maximum GW by almost 50% with the same rotor diameter and only a small increase in rotor inertia, this was of particular concern.

Therefore, these tests were dedicated to developing the optimum heavy GW autorotational flare technique for the MH-53J (SLEP/SBO) incorporating the 1.6° increase collective for inclusion in the Flight Manual.

The increased collective rigging also produced lower autorotational rotor speeds. All maneuvers were flown with the collective on the bottom stop. Initial testing was accomplished at approximately 2000 ft pressure altitude so that the maneuver would terminate by 1000 ft AGL. Subsequent tests were accomplished to the runway using a 200 ft AGL flare, with an initial loading of 42,000 lbs. The most promising combinations of pitch rate, max pitch attitude and airspeeds were also flown at 46,000, and 37,000 lbs. The test results are outlined below.

- Best Entry Airspeed--- 90 to 100 KIAS.
- Flare Rate---Approx. 4 deg/sec allowing aircraft to decelerate while paralleling ground varying slightly with GW.
- Flare Attitude--- A factor of pilot comfort tolerance. Higher flare attitudes lowered landing speeds. The max flare attitudes were 30 to 35 degs.
- Flare Altitude---Entered at 200 ft AGL, recovering by 40-60 ft AGL, but if accomplished to ground, would require a 140-160 ft minimum entry altitude.
- Flare Duration---The flare was continued (with the aircraft paralleling the ground) until the pitch attitude reached between 30 and 35 degs nose-up.
- Landing Attitude---Once the flare was completed, the nose was aggressively pushed over to a 10 deg landing attitude.
- Landing Airspeed---Actual touchdowns were not accomplished. The projected landing airspeed was a function of
- GW/CG and landing sink rate. *The aircraft is not nearly capable of a zero forward airspeed autorotational landing.*
- Rotor Speed RPM---N_r increased during the flare as long as a positive pitch rate was applied with an airspeed > 60 KIAS.

Configuration (GW/CG)	Steady State Nr (%)	Maximum Nr(%)
37,000	93	97
42,000	96	102
46,000	103-104	111-112

- *The Final Technique*---Enter the flare at an airspeed of 90 to 100 KIAS. Flare at 140 to 160 ft AGL. Flare at a rate that is sufficient to stop the sink rate (approximately 4 deg/sec) but not cause a ballooning affect. Continue to increase the pitch attitude until the aircraft has slowed sufficiently for landing, resulting in a max pitch attitude of 30-35 degs. When pitch rate has stops, aggressively pitch the nose down to a 10 degs (landing attitude). Pull approximately 1/3 collective pitch when reaching 10 degs landing attitude. After aligning the aircraft with the flight path, pull the remaining collective to cushion the landing. Plan to roll the aircraft on the ground at 30 to 45 knots.

VIBRATION MONITORING SYSTEM

The objective of the flight vibration survey was to gather baseline data for Maintenance Manual incorporation, to support the Vibration Monitoring System (VMS) usage for field vibration maintenance troubleshooting. VMS was developed by Chadwick-Helmuth Company for the MH-53J fleet. It monitors vibration levels at key airframe locations and interfaces with the Chadwick-Helmuth 8500 Rotor Track and Balance System and the ground based "VIBRALOG" vibration tracking software used by both the USAF and the US Navy. Prototype VMSs had been installed on two H-53's at Kirtland AFB for flight testing prior to the SLEP modification. The purpose here is to present some pre-SLEP and post-SLEP comparisons to illustrate the vibration improvements materializing from SLEP. See Fig. 6 for locations of the airframe and drivetrain velocimeters.

A few comparisons of the vibratory amplitudes in terms of inches per second (ips) in Figure 7. These are for a range of fuselage stations and cover the directions listed in the figure, some at 1/M and others at 6/M, all flown at 120 KIAS. The data shown in this figure is fleet averages from the Kirtland AFB data base. The reduction in vibratory levels shown is believed to result from aft fuselage stiffening and the incorporation of the ERH.

The SMFT data base is more specific covering steady stabilized conditions over the entire envelope.

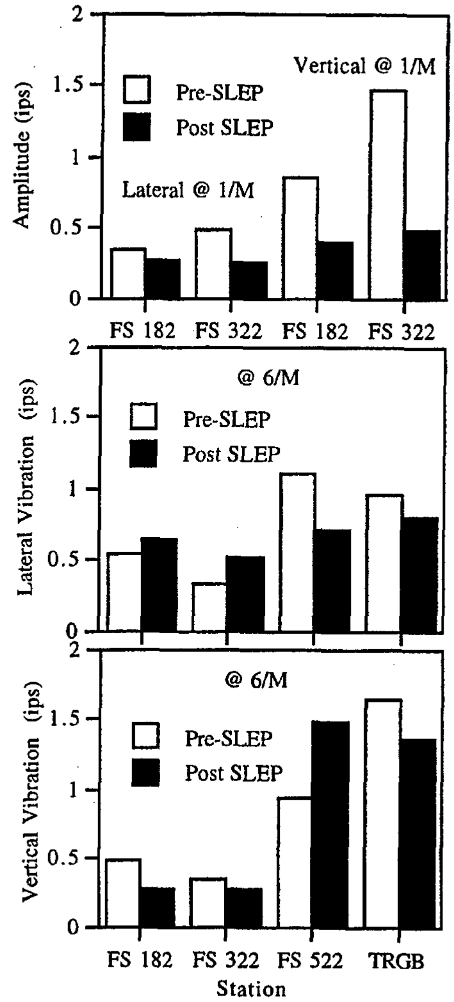


Figure 7. Vibration Levels.

FLIGHT STRAIN SURVEY

The total flight strain survey involved approximately 75 productive flight test hours covering the normal full flight envelope of the helicopter. Structural demonstration maneuvers are not included because they sometimes involve severe blade stall and are well outside maneuvers needed for determining component retirement times. Most every other flight condition involved in service use was flown. This included in-flight refueling, tactical mission maneuvers such as rapid return to target, slope landings, and a special tailrotor strain survey because the tailrotor components had a high probability of substantially reduced retirement times. The basic GW/CG envelope for various rotor speed / altitude conditions that constituted the flight strain survey is illustrated in Figure 8. The shaded area on the fwd CG side is that portion of the envelope that could not be released for load reasons, which resulted from the large nose down attitudes in high speed flight at these forward CG extremes.

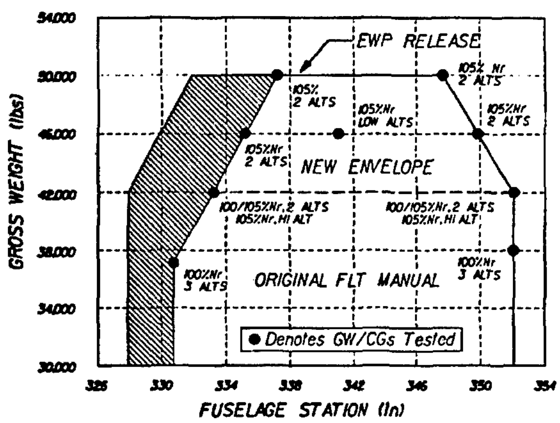


Figure 8. GW/CG Envelope.

The severity of blade stall is expressed by Sikorsky in terms of Equivalent Retreating Blade Tip Speed (ERTS). ERTS represents a normalization of blade loading for correlating vibratory loads (a function of GW, Hd, and g) with retreating blade tip speed (a function of Nr and true airspeed).

A calculated load factor/airspeed stall projection is at Figure 9, which was validated by these flight tests.

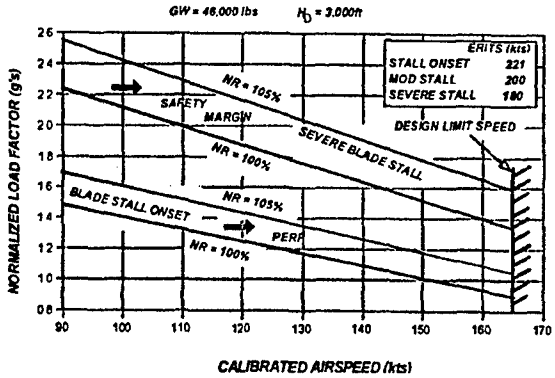


Figure 9. Load Factor/Airspeed Variations with Blade Stall.

RESUBSTANTIATION of CRTs

This flight strain survey data was used in the resubstantiation of component retirement times (CRTs) of the MH-53J (SLEP/SBO). Every dynamic component was considered as well as selected airframe components such as the tail pylon fold hinges. This resubstantiation was necessary because of the increased flight envelope, a revised mission usage spectrum, frequent use of 105% N_r to minimize loads, and improved technologies available for the acquisition and analysis of flight strain data since the last resubstantiation in the mid 1980's. The basic approach used was safe-life (deterministic) methodology, also known as the TOS/μ – 3σ method. Here TOS is top of data scatter, μ is the mean and $\sigma$is the standard deviation. Another technology upgrade was the extensive use of rainflow cycle counting of vibratory loads.

The results of this resubstantiation process were a "mixed bag" with regard to increase and decreases in retirement times. The normal expectation of reductions with increased GW was sometimes off-set by the use of higher N_r and redefined max allowable airspeeds (V_{NE}). Some parts that did not originally have retirement times were now subjected to mandatory removals; increases were justifiable for others. To list them here would require more detail than paper page limitations permit. The compelling point is that the resubstantiation significantly reduces maintenance risk and increases safety.

Additional effort ongoing at GTRI to reanalysis the CRT picture is using a probabilistic rather than deterministic methodology. The probabilistic methodology promulgated herein enables CRT as well as system level maintenance to be managed as a function of reliability (i.e. probability of operating without sustaining a fatigue crack) by utilizing statistical inference.

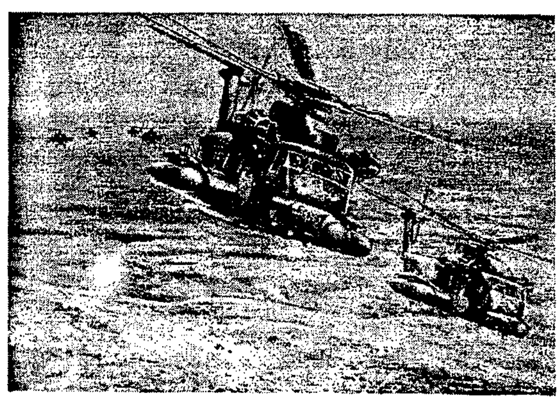
SUMMARY

The modernized MH-53J SLEP/SBO is the latest variant of one of the US Military's most important helicopters. It continues to service our nation well, frequently in harms way, as the center piece of the Special Operational Forces' rotary wing aircraft. Its makeup culminates a long line of successful H-53's maturing through a most effective modification process. The total mission capability of this SOF helicopter far exceeds the dreams of helicopter designers who first conceived it as a simple cargo helicopter. Its maximum gross weight has increased nearly 50% along with improvements in range capability. Incorporation of improved rotor blades and advanced T-64 engines has increased low speed climb and high speed maneuver capabilities.

At an approximate nonrecurring engineering cost of $40M (excluding government in-house management cost) and a unit recurring cost of $2.4M, it represents a most cost effective workhorse relative to a new design, particularly in light of the small fleet quantity (40+) needed for SOF. This does not counter the point that new technology can produce even better helicopters than the MH-53J, but recognizes the cost effectiveness of the modification process. It has served well as the nation waits for the truly advanced tiltrotor configuration, the V-22 Osprey, with much superior range and reaction times for SOF missions.

Whether or not this program could have been more efficient, if managed by an original equipment manufacturer (OEM) and a firm with the capability to perform hardware modifications at other than a government depot, will never be known. But the success of the approach used can not be denied.

The many MH-53J successes as a SOF helicopter have been well publicized by the US press, such as Somalia, Liberia, Bosnia, and now Yugoslavia; with combined humanitarian support and rescue efforts. In our opinion, the sketch below illustrates the pinnacle of its success. It can be seen flying a pathfinder mission, leading US Army Apaches into Iraq, on the first night of the air war which liberated Kuwait. These missions were to knock out radar warning devices in advance of other attacking coalition forces aircraft. This demonstrated its combat worth in the era of modern warfare. That's a *Special Operational Forces Rotorcraft Winner.*



ACKNOWLEDGEMENTS

The authors of this paper want to acknowledge the support of a few of the many individuals that contributed significantly to the MH-53J program and specifically to the preparation of this paper.

For a program of this magnitude many individuals (far to numerous to mention here), elements of industry, and government agencies worked diligently toward its success. The authors of this paper want to acknowledge three individuals who made specific contributions to this paper. The first is Mr. Charles "Chuck" Idone of the WR-ALC. formally the project manager during critical years of the modification work. His diligence in digging for important facts presented herein are greatly appreciated. The second is Mr. Doug Friend, of GTRI's Aerospace and Transportation Laboratory, who was the Georgia Tech onsite representative during the Structural Modification Flight Test program and who provided much of the information published herein. Finally, Ms. Jerry Clark is recognized for her untiring effort in putting to paper and editing our basic story.

The concluding photocopy is the art work of Ronald Wong, of St. Albans, Herts in Great Britain. He entitled it "Kickoff!" and graciously authorized its inclusion herein.

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The Canadian Air Force Experience
Selecting Aircraft Life Extension as the most economical solution

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Summary

Canada like several other countries has limited resources to trade-in its outdated and ageing fleets for state-of-the-art weapon systems. With the CF188 and the CP140, the Canadian Forces (CF) have chosen, as with the CF116 before, to perform a structural and systems upgrade. These upgrades will allow the aircraft to meet their operational requirements until the first quarter of the next century. The choice for this course of action is based on option analysis studies. In the end, fleet modernisation has proven to be the most economical solution. This paper will present the approach taken and the assumptions made for the various scenarios studied to reach that conclusion. Avionics packages are readily available off-the-shelf and in most cases the decision is based mostly on structural limitations. Hence in-service failures and results of full scale fatigue tests obtained through collaborative agreements can be a cost effective way to determine the cost of ownership of each fleet. The paper will briefly talk about the concept taken for the CP140 but will use the CF188 as the demonstration test case.

Background

In the early 1980s, the Canadian Forces rejuvenated their fleets of Anti-Submarine Warfare and Fighter aircraft. Two new platforms were purchased; the CP 140 ASW (Lockheed P-3) and the CF188 multi-role fighter (MacDonnell DouglasF-A/18-A/B). Those aircraft were selected, among other candidates from other manufacturers, after several years of evaluation. Needless to say the aircraft, when purchased, had equipment that was already on the verge of being superseded by improved state-of-the-art avionics systems. Both these aircraft had been expected to stay in service for 20 to 25 years. After such a period, it is reasonable to assume that they needed replacing. However, there are several factors affecting that decision, some technical and some economical. A significant area of concern is the suitability and supportability of the avionics equipment for the role of the aircraft. Secondly, the structure of the aircraft has to be properly examined to ensure a proper assessment of its current and future airworthiness is made. The easiest aspects to evaluate are the cost of replacing the aircraft with a new weapon system and that of upgrading the avionics suite. This exercise is relatively easy as it requires to make the list of desired capabilities and shop around for either the cost of a replacement aircraft or the cost of the desired avionics components and their installation. Even in the case of simply updating the avionics, the equipment packages are generally off the shelf and can be fitted on different platforms at a reasonable cost. The cost for avionics update is of the order of 10 to 20 times cheaper than the replacement of aircraft fleet depending on the fleet type and its size.

The determinant factor in the decision-making process, in most cases, is to assess the feasibility and cost difference between upgrading the aircraft structure to last long enough or to replace the fleet after the initial 20 year period. This last option may not always be possible. More and more countries, like Canada, are looking at purchasing weapon system platforms off-the-shelf. This implies aircraft manufacturers will have products available on demand. Unfortunately with the cost of new aircraft this is rarely the case and one may have no other choice than waiting for the latest model to appear on the market. As per a latest study in the United States, new platforms may become so expensive that they would be out of reach for most countries if not all. It is therefore required that tools are put in place to ensure Air Forces are in a position to make the best decision for the course ahead. The aim of the exercise, remains in

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

assessing capability for the aircraft structure to last long enough at a reasonable cost to make the avionics upgrade worth performing. To ensure proper amortisation of the cost of an avionics upgrade, the aircraft structure has to last for a sufficient amount of time after completion of the last upgraded aircraft. Although there are no firm rules on the acceptable number of years post avionics update, it has been estimated that for the Canadian Forces, an extension of approximately 10 to 15 years on a new avionics package is deemed acceptable. Based on this, a past study on the CF18 was performed and indicated that for each year of delay in replacing the CF-188 fleet beyond 20 years, while performing the avionics upgrade and structural modifications, had the potential for savings of the order of approximately C$30M[1] per year (1993 dollars).

Options review are often based on very cursory estimates and they do not represent well how a specific option can be made viable. Consequently, the CF has put in place some programmes and developed a series of tools to ensure its capability to assess the feasibility and cost effectiveness of upgrading the CF aircraft.

Life Extension Assessment Tools

Aircraft life extension is possible only if both the avionics suite and the structure can be sustained or upgraded at a reasonable cost. On the avionics upgrade, the specifications were produced and an implementation plan was put in place. The CF-188 avionics upgrade will be done in 3 phases starting in 2002 and will be completed in 2007 at a cost of approximately C$10M[1] per aircraft. The first phase will include upgrade to the Mission Computer, the GPS, the IFF and the radios. Phase 2 will incorporate upgrades to the radar, the DDIs, the Datalink and the Stores Management System. The last phase will provide upgrade to the Radar Warning Receiver, the EW Jammer, the chaff/flares dispensers, the missile approach warning system and the incorporation of a helmet mounted sight. Based on this information, assuming the aircraft structure can be sustained until near 2020, the investment for this work is acceptable.

To properly assess the structure, the first step is to have a well structured Aircraft Structural Integrity Programme (ASIP). The CF-188 has had a programme to that effect since the beginning of the life of the fleet. That programme was very effective from the outset and it provided data that clearly showed that the CF-188 would not be in service past year 2000. It would be the case unless significant changes to the flying operations were made and steps to determine the safe-life of the primary structure and the economical life of the aircraft were not taken. On the CF-188, the Fatigue Life Monitoring Programme (FLMP) was superimposed on ASIP. The additional responsibility of FLMP was to be able to monitor each mission severity and to educate operators. The aim was to maintain the same operational objective while reducing fatigue damage on the aircraft. On the CP-140, the same diagnosis was made, although the aircraft would be in service until 2010. The ASI programmes have allowed the CF to identify the best possible course of action. With both these aircraft, a Full Scale Durability and Damage Tolerance Test (FSDADT) was identified as the best course of action to determine the cost of maintaining the aircraft for a given period of time; the **"Cost of Ownership"**. The present paper will mostly highlight the CF-188 experience since the CP-140 test being performed in collaboration with the United States Navy (USN), the Royal Australian Air Force (RAAF) and the Netherlands Air Force, is still at the initiation stage. On the CF-188, the test is quite mature and results are already being fed into the long range planning of the fleet.

An additional incentive to perform a Full Scale Test on the CF-188 was that the predicted life from the manufacturer underestimated the usage made of the aircraft in service. Furthermore, in-service defects confirmed higher rate of damage and consequently, it was imperative that the cost of ownership be determined for the remaining life which was then at 4000 hours and for the desired service life. The prediction was based on the going rate of fatigue damage and the fact that the certification test was less severe than fleet usage. The objective was to determine the feasibility and cost for the aircraft to stay in service until it reached the required 6000 Equivalent Test Hours. The fatigue damage on the CF-188 is measured in terms of Fatigue Life Expended Index (FLEI), each hour on a Full Scale Test may not correspond exactly to one flight hour. Once the appropriate scatter factor is applied, the equivalency is done in FLEI rather than in hours. Consequently, assuming that the FLEI will be 1.0 at the end of the Full Scale Test, each aircraft will be measured against that number in relative terms of FLEI. Hence it is possible that some aircraft will fly more than 6000 hours and others less for a given damage index.

Cost Sharing through collaboration

Performing a FSDADT Test is a very expensive proposition and hence more countries will team up with each other to perform the work. In the present case, the Canadian Forces (CF) have teamed up with the Royal Australian Air Force (RAAF) under the terms of the International Follow-On Structural Test Project (IFOSTP). The structure of the arrangement is that Canada is performing testing on the Centre Fuselage (Figure 1) and Wings while Australia is performing testing on the Aft Fuselage. At half the cost the whole aircraft is covered. Obviously this comes with some compromises but due to the similar nature of the flying between both countries, the spectrum applied to the tests was a good representation of both countries flying. In the end, the cost of the whole project is equivalent to the replacement of slightly more than one aircraft.

The advantage of such a collaboration, is that it does not have to stop at the exchange of Full Scale Test results. In this case it has led to collaboration on a variety of other topics on which exchanges have proven beneficial and cost efficient for both countries. IFOSTP has also been the birth place for testing some life improvement processes such as shotpeening and complex 3-D composite patch applied to thick monolithic Aluminum structures. In the future, there is a potential to share further on the validation of repairs or replacement of major components on the aircraft.

Findings

The centre fuselage test, has accumulated 13,000 Spectrum Flight Hours (SFH). So far it has indicated a series of locations that will need to be addressed either through parts replacement or modifications. The aircraft was subjected to a major inspection at 12,000 sfh. The strategy used during that inspection was based on the failures found prior to reaching that time and their comparison with the results of the certification test conducted by MacDonnell Douglas and also on some in-service failures. It became obvious that some locations would pose a serious risk to the test article and to the fleet if a preventive modification was not developed and incorporated prior to test re-start at the end of that inspection. The risk on the test article was that a catastrophic failure could occur and jeopardise the whole test. The risk for the fleet was that a preventive modification would end up on the aircraft without prior testing on IFOSTP. After a risk analysis was performed, the critical locations were identified and modifications were developed for implementation during the down time.

The aircraft is managed based on a safe-life philosophy. Due to the nature of the material used on the main bulkheads of the CF188, which are the most critical areas, it is difficult to get any kind of damage tolerance from the structure. Aluminium 7050 is generally not very tolerant to damage. In the cases where symmetry was available between the 2 sides of the aircraft, the strategy was to modify the aircraft on one side, and allow the other side to develop the necessary damage to provide actual safe life of the feature location. The advantage is that a modification is being tested and certified, providing economical data, at the same time as the safe life of the primary structure is being established. This is meeting the two main objectives of the test which were to determine the life of the primary structure and the economical life of the aircraft.

As a rule, the centre fuselage test results were at the locations expected from the certification test and from in-service failure. However, most of them occurred much more prematurely and requiring some immediate action on the test and in the fleet. Figure 2 shows the breakdown of failures seen on IFOSTP in comparison with results from other sources or expected results from analytical predictions. In short, 96% of the failure sites were know but half of them occurred earlier than anticipated. Since the fleet was very close behind the test, immediate action was required to verify if some of the damages were present. The results of those inspections demonstrated that there exists good correlation between IFOSTP results and in-service findings. In-service findings were obtained from maintenance results since the aircraft came into service and also from a sampling inspection of 7 aircraft performed in 1997. Figure 3 shows the distribution of defects from the various levels of inspection. A total of 235 defects were found on the primary structure. 90 of them were discovered during depot level repairs, another 90 during squadron inspections and 55 during the Aircraft Sampling Inspection (ASI).

The results were quite significant as already several aircraft had passed their safe-life threshold and unless modifications were performed immediately, there was either an airworthiness concern or a potentially high economical impact in the future. Initially approximately 20 aircraft had to be removed from flying status due to potentially large economical consequences.

The most critical area of the CF-188 is the centre fuselage. There are 3 bulkheads retaining the wings and those bulkheads are fracture critical. It is also on the centre fuselage that the largest number of defects has been found and more are anticipated. There are other critical areas on the wings such as the spars and the attachment points and also on the aft fuselage; mostly on the Horizontal Stabilator attachments. Consequently, it will become obvious that most efforts and most of the cost will be concentrated on that area of the aircraft.

Converting findings into Cost of Ownership

Based on the results, a detailed review was performed of every single location on the aircraft and the associated cost for repair was estimated. This was the first step toward establishing the viability of performing repairs on the CF-188 to provide continuing airworthiness while extending the life. To date 111 locations have been identified as potentially requiring modifications. This number is based on the results of the Full Scale Test but also on the anticipated failure sites that have been identified as likely to cause problems during the rest of IFOSTP testing. The initial cost of these modifications was performed. That number seemed to indicate that embodying modifications would be a viable option. However, an option analysis was required to determine the most viable option.

Available Options – Initial Analysis

Four options were investigated:

a. replace the fleet before 2010;
b. perform a Centre Barrel Replacement (CBR) on the whole fleet before 2005;
c. perform all the modifications identified by IFOSTP results; and
d. perform a hybrid approach of modifications and CBR.

Option 1: Aircraft replacement was obviously envisaged. Aircraft such as the F-18 E/F and JSF were considered. The anticipated cost per aircraft was in excess of C$100M[1]. There was also a concern that the most suitable replacement aircraft would not be available in time to replace the CF188 fleet and that at least several modifications would have to be performed on the aircraft just to keep them flying until the new aircraft were delivered.

Option 2: The CBR option had been studied in the early part of the 1990s and initially the cost was deemed to be excessive. However, the USN has had to replace some centre barrels on their F-A/18 fleet and the actual cost was less than C$5M[1]. This option was now very attractive. However, the CBR did not cover all the defects. Some additional areas needed to be modified as they were known to be problematic, hence a CBR+ package was estimated. Once considerations for steady state installations were considered, the cost of this option was not expected to exceed the initial estimate for a CBR replacement of C$5M. But, this option did not address any wing or aft fuselage defects, which would have to de added.

Nevertheless, this is a very attractive solution. It is more elegant than performing a series of modifications to the structure and potentially, one gets an equal amount of life than with the original structure. Since several early deficiencies were rectified on the replacement barrel, several problematic areas would no longer be a problem.

On the other hand, there are many uncertainties associated with this option. The time to perform the replacement may preclude the CF to have the whole fleet done in a reasonable time. It would require several replacement lines that could make this option more costly than anticipated. And finally, there is no experience outside Naval Air Depot in North Island to perform this work.

Until the results of the wing and aft fuselage tests are known, this option is difficult to really estimate and to determine its overall benefits in comparison with other options. However, it is unlikely that the CF will be able to wait until the results of the wing and aft fuselage test results are obtained, which is likely to be toward the end of year 2000. In order to have the equipment in place and the CBR manufactured on time, the decision has to be reached by the fall of 1999. This option is still under review.

Option 3: Develop and implement the modifications based on IFOSTP results. The initial cost of ownership performed estimated that the centre fuselage modifications would add up to approximately C$1M[1]. However, it was difficult to assess the potential for integrating all the modifications and also to determine the time it would take to embody. Although this approach looked to be the more cost effective, there was insufficient information to complete the analysis.

Pursuing this option could have significant impact on the fleet availability if not properly setup. An other important point, is that the life of the aircraft would be only as long as the certification time on IFOSTP. Contrary to the CBR+ option, it would be less likely that the aircraft centre fuselage last longer than the anticipated 6000 Equivalent Test Hours (ETH).

Option 4: To allow for a potential phased approach to replace the current CF-188 fleet, a combination of option 2 and 3 could be used. A replacement programme could be put in place to have aircraft replaced over a slightly more extended period and hence take advantage of the additional life the CBR+ option would provide over the more limited life that would be provided by the modifications option.

Implementation Planning Tool

A priori, option 3 seems to be the most cost-effective option but option 2 cannot be rejected at this point. Significant planning is required to complete the structural upgrades in a timeframe consistent with the operational requirements and fleet Estimated Life Expectancy (ELE). Hence, there is also a requirement to integrate such a programme with the rest of the maintenance activities.

Requirement: To determine the best option to follow and to derive the most appropriate implementation plan, it was required to develop a Fleet Maintenance Planning tool. A system that will assist the fleet manager to make the most cost-effective decision for the planning of aircraft upgrades while minimising the impact on operational commitments and ensuring continuing airworthiness.

Objectives: The objectives for the development of such a tool were to:

a. optimise the limited resources available to support the CF-188 fleet while maximising operational availability;
b. provide the fleet manager with a global view of the numerous programmes and provide the flexibility of effectively incorporating all current and future maintenance initiatives;
c. provide optimised aircraft induction scenarios for optimal fleet usage and longevity;
d. perform pro-active planning to prevent unforecasted expenditures and sharp reductions in operational readiness;
e. provide visibility to priority tasks for appropriate allocation of resources; and
f. provide the user with a powerful decision making tool to assess potential changes in usage, number of aircraft, budgets etc..

End Product: The end product is a system that integrates/links engineering needs and supporting databases to aircraft maintenance and planning activities. It provides a user interface to the structural information system databases that allows decision-making through "what-if" scenarios. This has been translated into a programme called **"ALEX"** which stands for Airframe Life **EX**tension Programme. It has been developed to be flexible enough to allow maximum operational readiness at minimum cost. A conceptual diagram of ALEX is depicted in Figure 4. The programme takes information from both structural and avionics needs, adds in the resources available at the contractor and the cost of using those resources to deliver an optimised schedule and cost breakdown.

Capabilities: ALEX is capable of developing essential and optimal modification packages tailored for each aircraft. It provides realistic induction sequences that best meet budgetary constraints and operational requirements. Furthermore, it gives the customer and the contractor an appreciation of the long term material and personnel requirements through planning and scheduling packages.

Initially a total of 90 items were considered under this programme, each with different access and threshold requirements. This number of items would have been impossible to manage given the Level of Effort (LOE) constraints and required timelines. Also, performing everything in the order established would have proven too costly.

Especially initially since several modifications had to be implemented in the next 3-4 years causing a huge unmanageable demand during these next few years.

A slight change to the approach needed to be taken. Each defect was individually reviewed by a Tiger Team that grouped defects by locations and similar thresholds. The process was further refined using the revised lifing policy for the CF and performing risk assessments on some locations. The result was the development of the control points concept. Basically, **3 control points** were selected around major modification packages. Each control point is based on the safe-life of these locations and hence if left unmodified the aircraft would no longer maintain its airworthiness status. Figure 5 illustrates the centre fuselage of the CF-188 with the definition of the control points and their associated threshold based on CF usage. As shown on figure 6, the majority of the modifications produced by ALEX are in the centre fuselage of the aircraft and generally speaking the highest cost for those modifications is access to the location. ALEX permits optimisation of modifications based on access.

This programme is an effective and powerful tool for the fleet manager. It will allow him to decide the best course of action for each and every aircraft of the fleet. The level of modification for each aircraft will depend on the number of previous modifications, the lot number of the particular aircraft and the number of long term aircraft required for operational readiness. Some aircraft will receive the modifications associated with Control Point 1 while other aircraft will receive those associated with control point 3. Some aircraft may require the full implementation of modifications depending on ELE requirements. This is only possible due to the maturity and rigour of the Structural Integrity Programme. The Individual Aircraft Tracking capability of the CF-188 makes this level of refinement a reality that has not previously been possible. Furthermore, each aircraft will receive just the right amount of work to ensure operational sustainment.

Figure 7 illustrates the fleet decline based on the 3 control points if the required modifications were not embodied. It is an example only of a selected number of aircraft in the fleet. ALEX allows the possibility to predict aircraft availability and level of effort per year until the fleet is retired. It caters the induction schedule based on resources availability, aircraft usage and yearly flying rate. Figure 8 shows an example of a hypothetical ALEX run. The number of available aircraft has been modified to match with the resources available for each year.

The final decision

A business case is used to establish the best course of action. It seems the modification package will be the preferred option as it offers the most versatility. It allows to cater the level of effort for each aircraft and provides the most optimised solution. With selecting this option, it is possible that some aircraft receive a new centre barrel if it proves to be required to bring some aircraft to the required retirement date. Hence the decision will likely be option 4 using ALEX to guide the implementation of the different choices for each aircraft.

Conclusion

The Canadian Forces have been faced with difficult decisions with respect to maintaining a fleet of fighter aircraft well into the next century. The options ranged from replacing the whole fleet at a very high cost to performing various avionics and structural upgrades at a much reduced cost. The decision could not be made without appropriate information and the development of the right tools. The data was obtained through a well managed ASI programme which has included a Full Scale Test and the development of a decision making system that allows to run changing scenarios. The main advantage of the tools developed provide the flexibility to cater the right level of upgrades to each individual aircraft hence optimising all the available resources.

Although the final decision has not been made, all the tools are in place to make a business case that will likely lead to the performance of an avionics update supplemented by a series of structural modifications.

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[1] All cost numbers have been normalized to provide relative comparisons between the various options and do not necessarily represent actual costs.

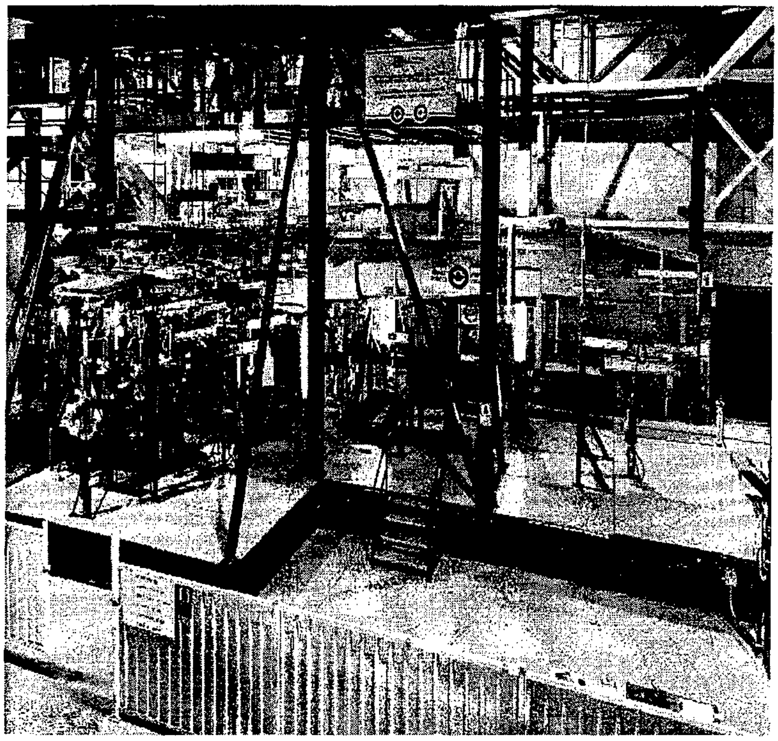

Figure 1 – IFOSTP Centre Fuslage Test Article
Bombardier Aerospace Defence Systems - Mirabel

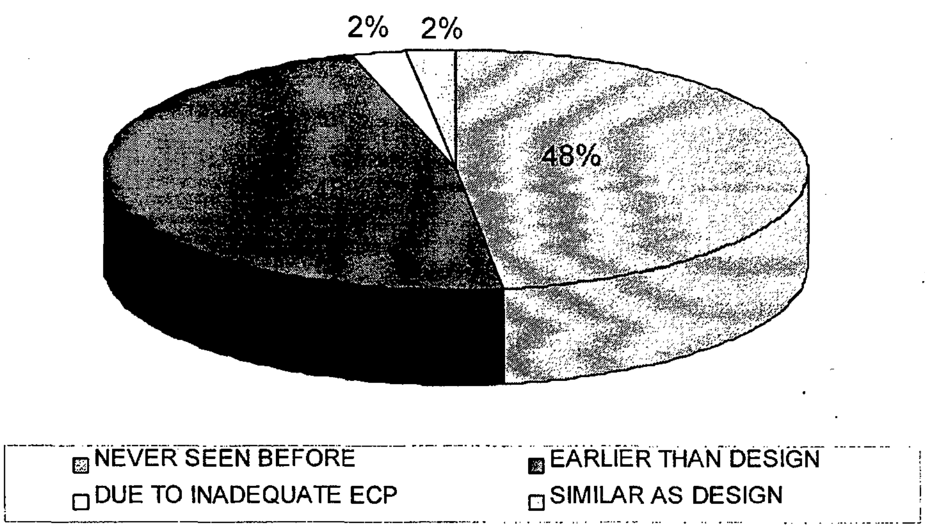

Figure 2 – IFOSTP Results Comparing to Known and Anticipated Failures

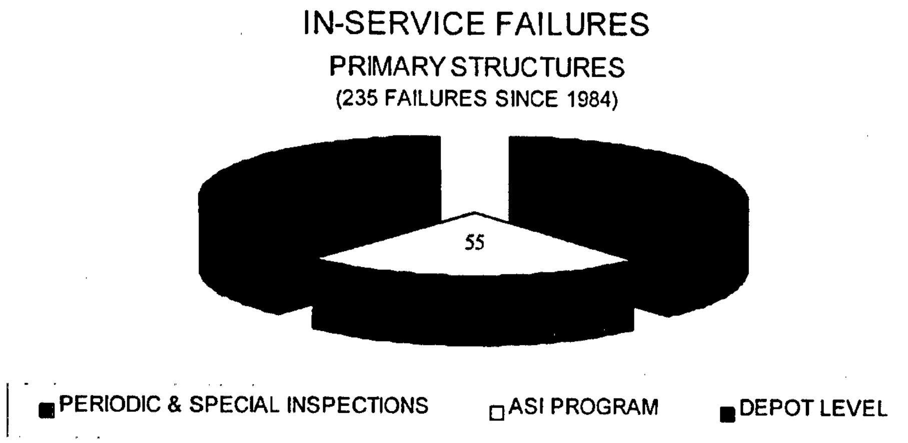

Figure 3 – Distribution of In-Service Failures

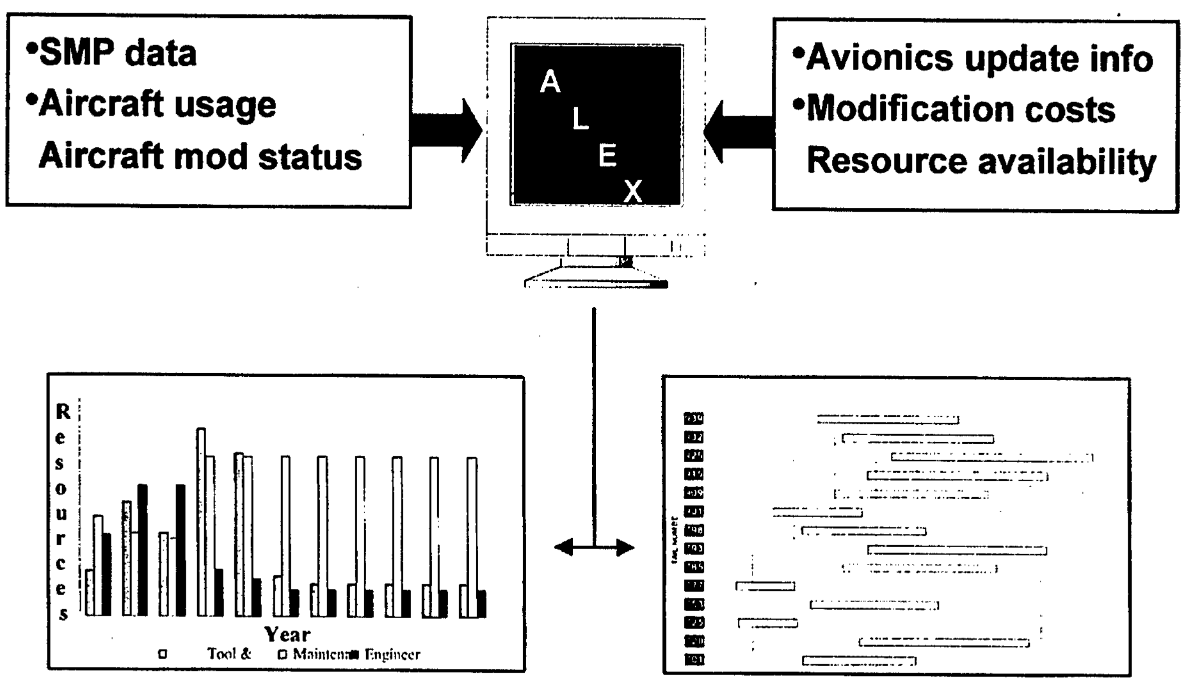

Figure 4 – ALEX - Modification Line Planning

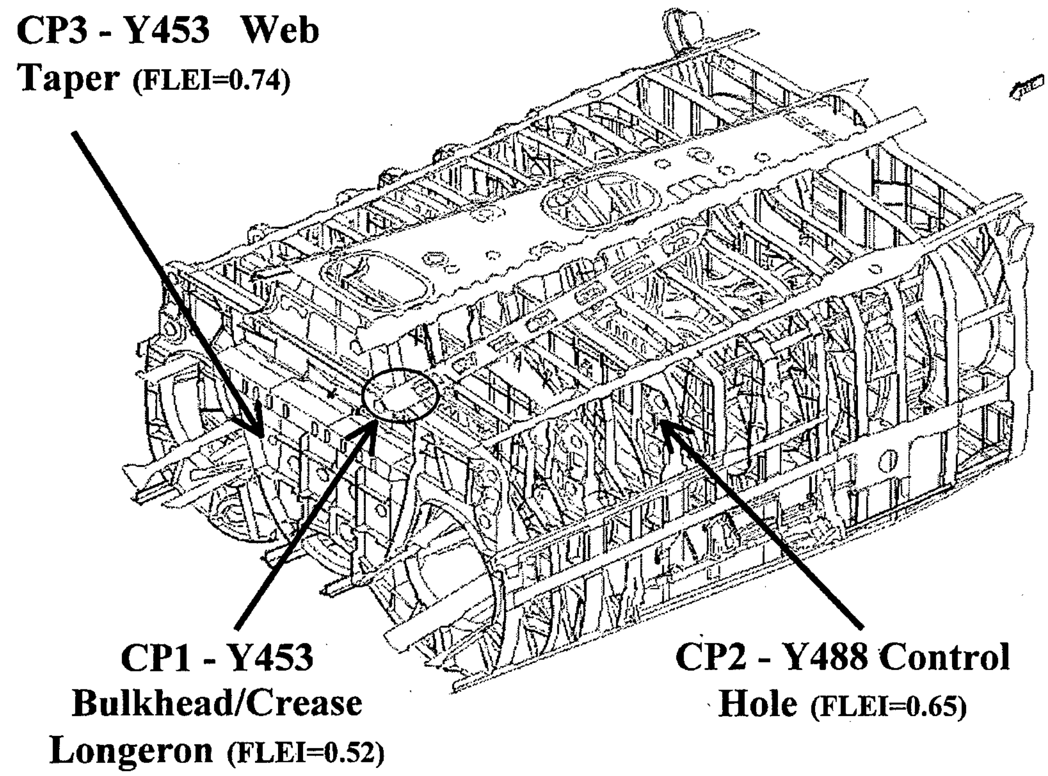

Figure 5- CF188 Centre Fuselage – Control Points Location

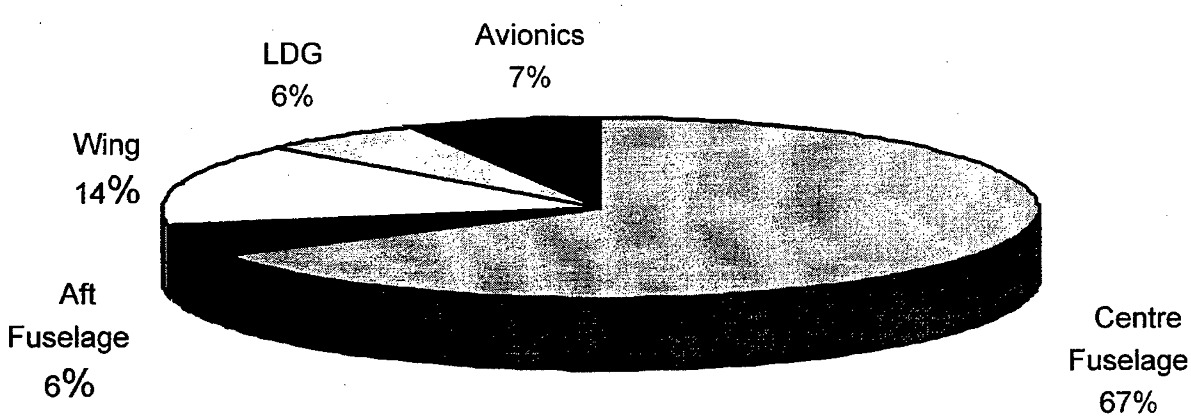

Figure 6 – Modifications Distribution

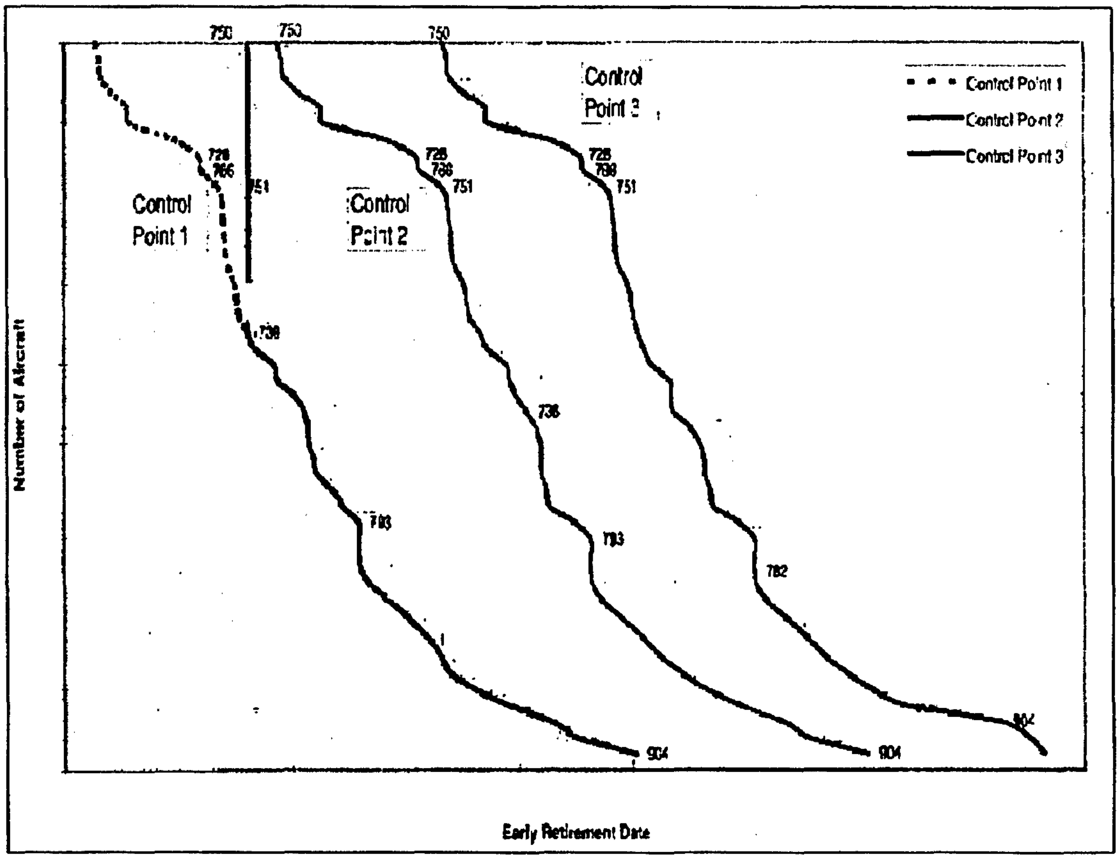

Figure 7 – Aircraft Retirement Dates Based on 3 Control Points

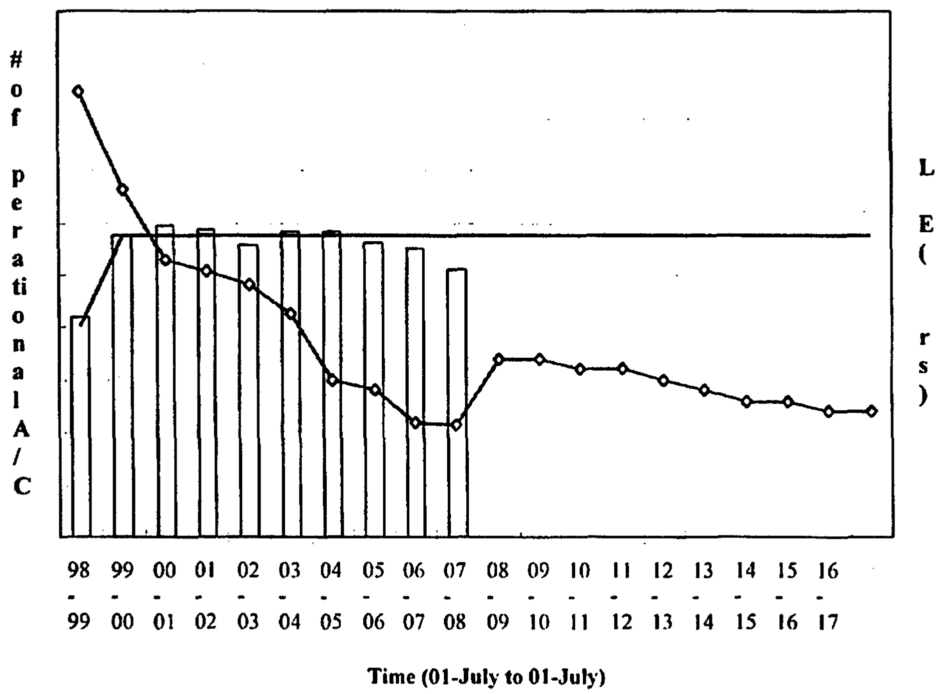

Figure 8 – Example of an Optimised ALEX run
Yearly LOE vs Operationally Available Aircraft

Transall C-160 Life Extension and Avionics Upgrade Programs

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Summary:

Objektives: Since 1967 the Transall C-160 is the transport aircraft of the German Air Force. After carrying out of life extension measures, avionics upgrade and other improvements of the technical equipment, the Transall C-160 can be operated under economical conditions far beyond 2010.

Description: Life extension measures for C-160 started in 1984 (LEDA I and LEDA II). These measures were only carried out for the wings. After taking apart the aircraft in this high scope, more than 30% of complaints were discovered in comparison to the normal preventive maintenance activities. As a result an investigation of aircraft areas and zones not yet subject to inspection measures (PUNIB) was carried out. PUNIB was the basis for LEDA III. In LEDA III the whole structure of the aircraft was inspected. In this manner the life time of the aircraft was extended step by step. Primarily the specification of the original air frame lifetime was restricted to 1995 or 8000 flights (LEDA I, LEDA II). After LEDA III the lifetime for C-160 was extended to 2010 or 12000 flights. Because of the spare part situation avionic upgrades in 1987 and the replacement of the flight management system (FMS) and the flight control/flight director system (FCS) in 1993 in combination with the replacement of the wiring was carried out. These measures will be finished in 1999. Over and above, the replacement of the intercom system, the improvement of the selfdefense suite and the integration of a traffic alert and collision avoidance system (TCAS II) as well as other technical measures will be taken. These increase the reliability and improve the precision of the mission management. Moreover the spare part situation was improved since the mid 80's by the aircraft update programmes.

Results: The life extension technical measures and the avionic upgrade programs increased the reliability, improved the precision of the mission management and in the longer term the provision of spare parts. Because of the life extension measures and the avionic upgrade programs the C-160 fleet can be operated beyond 2010. The last aircraft needs to be grounded not before 2018. Over 50 years in service, which proves the effectiveness of the discribed measures and indicates that upgrade programmes can be an economical alternative to the procurement of new systems.

Content:

1. Brief History of Transall C-160

On April 16, 1959 the production of a total of 218 aircraft was started by signing the Transall Cooperation Contract. Major participants in design and production were the companies:

- Nord Aviation
- Hamburger Flugzeugbau GmbH
- „Weser" Flugzeugbau GmbH
- Prof. W. Blume Leicht- und Flugzeugtechnik GmbH

Between February 1963 and February 1964 the first flights of 3 prototype aircraft took place. 169 aircraft of a first series were produced and delivered in a timeframe from 1967 to 1973:

- 50 A/C for France
- 110 A/C for Germany
  (later 90 A/C for GAF, 20 A/C for TUAF)
- 9 A/C for South Africa

During the initial production series the three partner companies produced individual major components such

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

as fuselage front, center and tail sections in addition to main wings and empennage. Each company shipped their produced components to the other partners where each then did final assembly at lines in Hamburg, Bremen and Bourges.

Since 1979, within 7 years, 35 aircraft were produced in a second series:

- 29 A/C for France
  (25 A/C standard version, 4 A/C special mission)
- 6 A/C for Indonesia

Contrary to the initial series, the second series consisted of the same production sharing in Hamburg, Bremen and Toulouse, however with only one final assembly line in Toulouse.
The A/C of the second series differed from the first series A/C as follows:

- Capability for aerial refuelling (25 A/C)
- Tanker mission (10 of 25 A/C)
- Modern communication system
- Modern navigation system

Here are the main technical data of the Transall C-160:

Wing span	40.0 Meters	
Overall length	32.4 Meters	
Total height	11.8 Meters	
Max. T.O. weight	49.2 Tons	(1st lot)
	51 Tons	(2nd lot)
Max. payload	16 Tons	
Max. fuel capacity:	16,000 Liters	(1st lot GER)
	19,000 Liters	(1st lot F)
	28,000 Liters	(2nd lot)
Cruise speed	485 Km/h	
T.O. distance	650 Meters	(43.8 Tons)
Landing distance	580 Meters	(40.1 Tons)
Max. range	4,560 km	(1st lot GER)
	5,415 km	(1st lot F)
	7,980 km	(2nd lot)
Usable cargo space	139.9 m^3	

The German Air Force Transall C-160 was designed for the following missions:

1. Cargo (includes dropping of cargo from low to extremly low heights)
2. Transportation of personnel
3. Dropping of paratroopers
4. Transportation of wounded personnel
5. Fire fighting missions

Today, the French C-160 aircraft are maintaned by AIA/CIT (Atelier Industriel Aéronautique/Cellule Industrielle Transall) in Clermont-Ferrand. The engineering is done by Aerospatiale in Toulouse.

The German C-160 fleet is supported in depot level maintenance and engineering by DaimlerChrysler Aerospace in Manching.
The logistical support is done by the weapon system companies AIA/CIT, Aerospatiale and Dasa M which includes besides depot level inspections, modifications, upgrades and supply of spareparts and documentation.

2. Life Extension Measures

According to the „Technical Specification Series Aircraft", the lifetime of the Transall C-160 was designed for 5,000 flights, thereof 625 low level flights. At that time the calculation was based on 2 flight hours per flight. Since the first aircraft were delivered to the German Air Force in 1967, the aircraft could have been used until 1990 (theoretically). In reality, however, one flight took only an average of 1.22 flight hours. This resulted in a reduction of the in-service time by almost 40%. This forced an early conception of adequate measures, that would allow to operate the A/C in excess of 5,000 flights. This resulted in the so-called LEDA measures, where LEDA is a German acronym for „Lebensdauerverlängernde Maßnahmen" (Life Extension Measures).

The following measures were taken with respect to the structure of the A/C:

2.1	Preparatory work for LEDA	
2.2	LEDA I / II	1984 - 1990
2.3	PUNIB	1987 - 1988
2.4	LEDA III	1988 - 1999

2.1 Preparatory Work for LEDA

2.1.1 Tests on the Dynamic Fatigue Test Airframe

Extended tests were run, among others, the induction of artifical cracks with defined length and a certain crack configuration. The progress of the crack was monitored under operational conditions and with different loads:

- purely exterior load,
- purely interior pressure load changes and
- exterior load overlapping with interior pressure load and changes.

The tests were performed on the dynamic fatigue test airframe especially in the areas of the center fuselage, wing and after fuselage section. The result of the tests corresponded very favorably with the calculated crack progress data.

2.1.2 Inspections of Older Aircraft

Aircraft with an average of 2,800 flight hours were inspected to determine the degree of damage of these aircraft. Critical areas were examined with respect to vibration cracks and corrosion, respectively. For example, 500 rivets on the underside of the wing were removed and the holes tested with eddy-current.

2.1.3 Minor Tests for Determining Adequate Cold-Working Procedures

Sample mandrels were tested to determine the optimum degree of the cold working required. Two different expansion procedures were considered:

- the Aerospatiale (AS) procedure and
- the Boeing Split-Sleeve Cold-Expansion procedure.

Using the AS procedure, the expansion tool acts directly on the wall of the fastener hole and there is the risk of contamination, grinding and scratching.
Using the split-sleeve cold-expansion procedure the mandrel acts on a sleeve inserted into the drillhole and therefore indirectly on the wall of the drillhole. The resulting burrs on the slit of the sleeve can be removed by a deburring tool.
The objective to extend the lifetime distinctly can be achieved with both procedures.
The Aerospatiale procedure was used on the French Transall C-160's. Germany decided to use the split-sleeve cold-expansion method since the improvement factor was considered to be higher with this procedure.

2.1.4 Component Tests

The objective of the tests was to determine the influence of the expansion of rivetholes on the lifetime of individual components. The result of those component tests was, that in certain areas a high degree of stiffness and high level of tension existed, for example in the area of structural doublers. By cold-working of this area alone, life would be extended up to a factor >2. This also means, that 8,000 flights could have been reached without additional measures like LEDA, if the holes would have been cold-worked during aircraft production.

2.2 LEDA I/II

LEDA I/II includes life extension measures in the wing area. This encompasses the replacement of 5,148 close tolerance fasteners, 630 standard rivets and 3,168 rivet holes cold-worked per aircraft. Additionally doublers were installed on the wing center sections and the outer wings. LEDA I/II measures were taken between 1984 and 1990 after 4,200 flights.

2.3 PUNIB

PUNIB is a German acronym for „Programm zur Untersuchung nicht inspizierter Bereiche" (investigation of aircraft areas and zones not yet subject to inspection measures). Using non-destructive inspection procedures (eddy-current, roto-test, magnaflux, dye-penetration procedures), visual and tolerance inspections were made in areas that had not been subject to planned inspections according to the inspection manual up to that time. The program was decided on in 1986, the contents defined, and performed on 1 Turkish and 3 German aircraft in 1987/1988. The result of these tests was, that extensive measures are required, especially in areas outside environmentally controlled fuselage.

2.4 LEDA III

The PUNIB tests formed the basis for the LEDA III program, devided into Immediate Action Measures and Follow-On Measures.

The Immediate Action Program was executed from 1988 to 1992 in order to limit the effects of the damage. These were measures like empty space preservation, corrosion treatment and changes of material, etc.
For short, empty space preservation is described as an example:
In this case, the most suitable anticorrosion chemical had to be found, for the materials used on the Transall C-160 for:

- Accessible areas (horizontal and vertical fin)
- Non-accessible areas (ailerons, flaps)
- Installed parts (struts, control rods).

Prior damaged samples were exposed, for example to salt fog or spray water tests. The best corrosion protection was achieved by the chemical DINITROL AV 5 and DINITROL AV 100, which generates a firm protective film.

The second part of LEDA III, the Follow-On Measures, was executed from 1991 to 1999.

Results:

By means of life extension measures (LEDA), the A/C life was successfully and successively extended:

- LEDA I – measures (cold working in wing area) to 8,000 flights, utilisation up to 1995
- LEDA II – measures (reinforcement of the wing area)
- LEDA III – prevention and corrective measures on the entire airframe to more than 12,000 flights and an utilisation of at least up to 2010.

The German Transall C-160 fleet has nowadays an average airframe life time of 29 years and an average of 8,000 flight hours airframe stress (in comparison, the French fleet of the first production series has 15,500 flight hours at the average).

3. Avionics Upgrade Measures:

Since the introduction of the Transall C-160 in 1967, approximately 2000 upgrades and modifications were incorporated:
- approximately 60 % with respect to the structure
- approximately 40 % with respect to the equipment.

These measures encompass the following aspects:

3.1 Avionic modifications
3.2 ANA/FRA and new wiring
3.3 ELOKA, INTERCOM, TCAS II.

Objective:
It was the objective of the modifications to replace avionic equipment that could no longer be supported and simultaneously to upgrade the avionics to the present state-of-the-art. Also, in order to obtain a centralised control and display system, which allows the central operation of the communication and navigation system via CDU (Control and Display Unit).

3.1 Avionic Modifications

Within the scope of life time extension measures, parts of the avionics system were renewed in parallel. In a first step, HF, WX-radar and radio-altimeter were replaced by newer equipment and additionally a SELCAL and data transmission system were installed.

3.2 ANA/FRA and New Wiring

Two objectives were behind the installation of the ECM-resistant Autonomous Navigation (ANA) and Flight Control/Flight Director (FRA) System.

1. Objective: Improving the reliability and accuracy of the navigation system / Reduction of maintenance cost

This was achieved by the:

- Replacement of the obsolete Syp 820, C11, Doppler, PHI and LORAN equipment by the Autonomous Navigation System (ANA) consisting of
  - LINS: Laser Inertial Navigationssystem
  - GPS: Global Positioning System
  - ADC: Air Data Computer
  - EHSI: Electronic Horizontal Situation Indicator and the
- Installation of a new Flight Control/Flight Director System (FRA):
  - SPZ 450: new Autopilot
  - AHRS: Attitude/Heading Reference System

2. Objective: Change of the operating and crew concept

- New operating concept:
  As mentioned before, after the installation of the ANA/FRA system, the entire communication and navigation system can be centrally operated and controlled by the pilot and the co-pilot via Central Display Units. In order to do that, it was necessary to connect the various equipment of the Autonomous Navigation system via a data bus according to MIL STD 1553 B.
- New crew concept:
  There is no longer one unflexible crew concept, but there are two alternatives:
  - a 4-man crew for tactical missions and short distance flights and
  - a 3-man crew for medium and long distance flights (without navigator)

With these alternatives, personnel and mission planning becomes more flexible and, on the other hand, the number of personnel can be reduced.

The time schedule for the ANA/FRA-program is described by the following mile stones:

II/87	Completion of concept phase
III/89	Completion of preparatory work development phase
IV/89 – IV/93	Development phase, kit-proofing, and integrated testing
III/93 – XII/99	Incorporation in series A/C

In parallel to the ANA/FRA installation in the C-160, the entire A/C wiring was replaced 1:1. This amounts to approximately 40,000 meters of cables per A/C.

3.3 ELOKA, INTERCOM, TCAS II

3.3.1 ELOKA

In order to improve the self-protection capability of the Transall C-160, an anti-aircraft-fire-protection system using kevlar and armoured plates was incorporated into all 86 A/C of the German C-160 fleet from 1992 to 1999 and a self-defense system was installed into 24 A/C.
The self defense system consists of the following components:

- Radar Warning System
- Chaff/Flare Dispenser
- Missile Approach Warning System
- Electronic Warfare Management System

3.3.2 INTERCOM

In 1998/1999 the kit-proofing of a new INTERCOM system was completed. It will be incorporated into the fleet starting in 2000. This retrofit measure became necessary since the logistical support for the 40 year old intercom system was no longer secured and because of additonal operational requirements of the German Air Force.

3.3.3 TCAS II

TCAS II will be required by law for commercial A/C with more than 30 seats and/or more than 15 tons of weight within European air space after January 1, 2000. Furthermore a USAF C-141B Starlifter collided with a Tupolev TU-154 of the GAF off the African west coast on September 13, 1997. A collision that might have been avoided by TCAS. For this reason, the German Transall C-160 will be equipped with a collision warning system. It will be installed within the next 3 years.

Besides these projects, measures like the renewal of the VOR/ILS and replacement of the IFF transponder STR-700 by STR-2000 are presently prepared.

4. Life Extension Measures as an Economic Alternative ?

Life extension measures and avionics upgrade as described became necessary in order to keep the fleet operational in the short and long terms.

These measures improved

- the availability of the A/C and
- the accuracy of the mission management.

In the long run,

- an improvement of spare provisioning and
- the extension of the life time of the C-160 fleet beyond 2010

was achieved.

According to the present planning, the last A/C is not to be phased out before 2018. An average service life of more than 50 years proves the quality of the described measures.
The question, however, may be discussed, whether extending the life time by 150% or 30 years is in general an economical alternative, compared to the introduction of a new system. This must be considered and calculated individually for each weapon system. The costs for all the upgrade programs were less than 20% of the A/C purchase investment cost. In comparison the A/C in-service time was extended more than 150%. This means that, in case of the Transall C-160, the upgrade programs were and are a cost-effective alternative.

List of Abbreviation

A/C	Aircraft
ADC	Air Data Computer
AHRS	Attitude/Heading Reference System
AIA	Atélier Industriel Aéronautique
ANA/FRA	Autonome Navigationsanlage und Flugregelanlage Autonomous Navigation and Flight Control/Flight Director System
CDU	Control and Display Unit
CIT	Cellule Industrielle Transall
EHSI	Electronic Horizontal Situation Indicator
ELOKA	Elektronische Kampfführung Electronic Warfare
F	France
GAF	German Air Force
GPS	Global Positoning System
ILS	Instrument Landing System
INTERCOM	Intercommunication System
LEDA	Lebensdauer verlängernde Maßnahmen; Life extension measures
LINS	Laser Inertial Navigation System
NDI	Non-destructive inspection procedure
TCAS	Traffic Alert and Collision Avoidance System
TUAF	Turkish Air Force
USAF	United States Air Force
PUNIB	Programm zur Untersuchung bisher nicht inspizierter Bereiche; Investigation of aircraft areas and zones not yet subject to inspection measures
VOR	Very High Frequency Omnidirectional Radio Range

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	10 May 1999	Conference Proceedings

4. TITLE AND SUBTITLE

The C.SAR Cougar, an example of optimization of an existing helicopter

5. FUNDING NUMBERS

F61775-99-WF007

6. AUTHOR(S)

P. Jaillet Cabrit

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

EUROCOPTER
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France

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES

EOARD
PSC 802 Box 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

CSP 99-5007

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

ABSTRACT (Maximum 200 words)

The COUGAR is a military transport helicopter of the 9-ton class, which is largely utilized by 45 countries of the world. Since the launching of the EUROCOPTER helicopter there have been production enhancements while preserving the quality for combat missions. The principal requirements for COUGAR in combat missions are: a long maximum operating range; a capacity to fly at "any time" of day and night; and a low level of detection and vulnerability as well as good resistance in the event of a crash.

14. SUBJECT TERMS

EOARD, aircraft, helicopter, combat

15. NUMBER OF PAGES

N/A

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

Le Cougar C.SAR, un exemple d'optimisation d'un hélicoptère existant
(The C.SAR Cougar, an example of optimisation of an existing helicopter)

par Ph. CABRIT, P.JAILLET & T. GIACINO

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0. Sommaire :

Le COUGAR est un hélicoptère de transport militaire de la classe des 9 tonnes qui est largement utilisé dans différentes versions par de nombreuses armées à travers le monde (45 pays clients). Depuis le lancement de cet hélicoptère, EUROCOPTER a développé de façon constante des améliorations de cet appareil afin de faire bénéficier à ses utilisateurs des équipements les plus modernes existants sur le marché tout en conservant ses qualités militaires de base. Un effort particulier a été effectué pour disposer d'un appareil très performant pour la mission "SAR"(*) de combat.

En effet, ce type de mission impose un appareil ayant une charge utile élevée, un rayon d'action important et une capacité de vol "tous temps". D'autre part un faible niveau de détectabilité et de vulnérabilité ainsi qu' une bonne résistance en cas de crash sont nécessaires. Ce sont des caractéristiques essentielles dont dispose le COUGAR et qui ont permis de définir à partir des versions de base un hélicoptère bien adapté à ce type de mission par l'installation d'équipement appropriés: système de navigation, système d'aide à la recherche (radar 360°, FLIR, phare infra-rouge, PLS Personal Locator System), système de contre-mesures (détection, leurres), armement d'auto-protection (canon axial de 20 mm, mitrailleuse en sabord). D'autres améliorations ont été étudiées qui permettent d'accroître encore ces performances si la mission le nécessite. Il s'agit de la définition d'un concept d'emploi permettant la réalisation de la mission à des masses très élevées, d'un accroissement supplémentaire de la capacité carburant et du développement d'un système de ravitaillement en vol.

(*) SAR = Search and Rescue (Recherche et Sauvetage)

1. Introduction :

Les situations de crises rencontrées par les pays occidentaux au cours de ces dernières années ont montré la nécessité de disposer d'hélicoptères équipé pour la mission "SAR de combat", c'est-à-dire la récupération à grande distance de personnes en zone ennemie. En temps de paix, ce type d'hélicoptère est nécessaire pour des opérations SAR à des distances très importantes de la côte ou dans des zones d'accès difficile.

Les principales exigences pour ce type de mission sont :

- long rayon d'action
- sécurité maximale
- capacité de vol "tout temps" de jour et de nuit
- protection accrue des systèmes vitaux de l'hélicoptère
- discrétion
- flexibilité d'utilisation.

Le COUGAR, hélicoptère de transport militaire éprouvé disposant de performances élevées, constituait une base de développement idéale pour obtenir le type de performances recherchées pour un appareil SAR de combat.

2. Principales caractéristiques du COUGAR :

Le COUGAR est un hélicoptère de transport militaire dont les principales caractéristiques sont les suivantes :

Masse totale : 9000 à 9750 kg (suivant les versions)
Charge utile + carburant + équipage + équipement de mission: 4200 à 4800 kg
Moteur TURBOMECA MAKILA de 1400 à 1573 kw (suivant les versions)
Vitesse maxi : 150 kts

Volume cabine : 13,4 à 15.5 m^3
Plancher cabine plat 9,20 à 10,50m^2
Longueur cabine 6,81 à 7,87 m
Accès à la cabine par 2 grandes portes latérales coulissantes et par une trappe d'accès arrière.

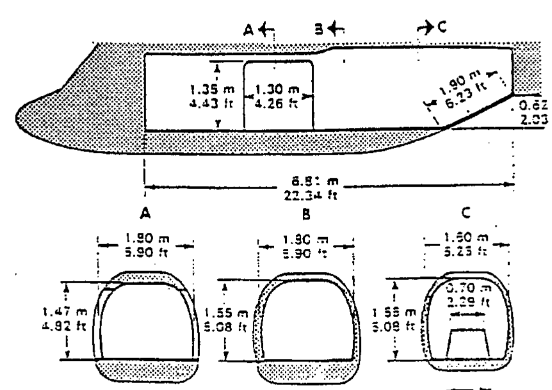

Figure 1: dimensions principales de la cabine

Paper presented at the RTO SCI Symposium on "Aircraft Update Programmes. The Economical Alternative?", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

Le COUGAR a été qualifié par les Services Officiels militaires Français (DGA) dans différentes versions. Il répond en particulier aux exigences militaires suivantes:

- tenue au crash de la structure 10,2 m/s à 9000 kg
- train d'atterrissage à haute absorption d'énergie
- circuit carburant anti-crash
- sièges anti-crash (équipage et occupants cabine)
- vulnérabilité réduite.

De plus, le véhicule de base est conforme aux exigences de la certification civile FAR 29 ce qui offre aux utilisateurs militaires un haut niveau de sécurité.

Le COUGAR dispose de capacités au vol "tous temps":

✓ équipement complet pour le vol aux instruments,

✓Cockpit compatible du vol avec jumelles BNL

✓vol en conditions givrantes, deux niveaux de protections sont offerts :

- vol en conditions givrantes limitées,
- système de dégivrage complet (avec dégivrage / antigivrage des rotors) permettant le vol en conditions givrantes sans limitations.
  Ce système est approuvé pour ce type d'utilisation par la DGAC française et la FAA.

✓ mise en oeuvre et fonctionnement jusqu'à des températures de - 45°C,

✓ fonctionnement en atmosphère sableuse avec une protection renforcée des entrées d'air moteur grâce à des filtres équipés d'éléments séparateurs à effet vortex. (entrées d'air polyvalentes)

3. Circuit carburant :

Le Cougar dispose d'une capacité réservoir carburant interne très importante de 2280 l (réservoir de base 1960 l. + un réservoir optionnel de 320 l.). Il peut être ajouté des réservoirs d'ailettes (situés au-dessus du train d'atterrissage principal) d'une capacité de 2 x 325 l. Ceci représente une capacité totale de 2930 l. Tous ces réservoirs sont constitués d'outres anticrash. L'ensemble de ces réservoirs sont installés à l'extérieur du volume de la cabine. Les réservoirs peuvent être rendus auto-obturant au calibre de 12,7 mm.

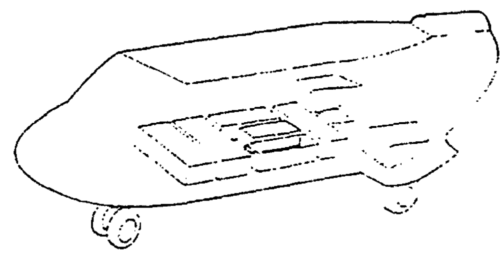

figure 2: Configuration des réservoirs internes + ailettes

De plus quatre réservoirs de 475 l. chacun peuvent être installés à l'intérieur de la cabine, ceux-ci porte la capacité totale de carburant à 4830 l.
Ces configurations de réservoirs confèrent au COUGAR des distances franchissables remarquables:

(avec carburant interne)	860 km (465 Nm)
(avec réservoirs d'ailette)	1140 km (630 Nm)
(avec réservoirs en cabine)	> 2100 km (1130Nm)

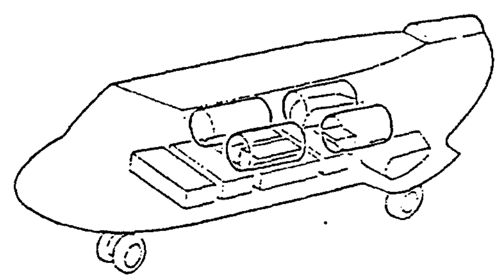

Figure 3: Configuration des réservoirs de cabine

L' appareil peut-être équipé en option d'une perche télescopique de ravitaillement (optionnel en cours de développement sur certaines versions) permettant d'effectuer un remplissage en vol. Celui-ci s'effectue avec l'aide d'un avion ravitailleur à 4000 ft à une vitesse de 130 Kts.

4. Auto protection :

L'appareil présente un niveau de vulnérabilité réduit à l'attaque des armes adverses basé sur la logique suivante :

- éviter la détection,
- en cas de détection, éviter d'être touché (être averti de la détection),
- en cas d'impact, éviter un dommage majeur,
- en cas de crash, assurer un taux de survivabilité élevé.

La faible détectabilité est assuré par la manoeuvrabilité et la capacité en vol tactique, un faible niveau de bruit (inférieur à la limite OACI - 3 dB), une faible réflectivité radar (utilisation de matériau composite approprié pour des parties importantes de la structure: capotages, ailettes, empennage) et l'utilisation d'un déviateur/dilueur de jet sur l'échappement des moteurs.

Un système de contre-mesures électroniques permet d'être averti d'une éventuelle détection: détecteur d'alerte radar, détecteur d'alerte laser détecteur de départ de missile.
Des systèmes de leurres (brouilleur infra-rouge, brouilleur électromagnétique) permettent d'éviter d'être touché en cas de détection.

La conception de l'hélicoptère et de ces ensembles principaux lui confèrent une faible vulnérabilité :

- pales des rotors principal et arrière réalisées entièrement en matériau composite tolérantes aux impacts de projectiles,
- blindage de protection de l'équipage,
- réservoirs carburant auto-obturants.

Un niveau de sécurité optimal est assuré en cas de crash par :

- le niveau de protection de la structure conçue pour résister à une: vitesse d'impact de 10,2 m/s à la masse maximale autorisé en vol normal,
- la conception du train d'atterrissage assurant une grande absorption d'énergie,
- les réservoirs carburant équipés d'outres anti-crash.

La cellule complète du COUGAR a fait l'objet d'un essai de crash.

5. Equipements pour la mission C-SAR

5.1. Système d'aide au pilotage et de navigation :

Les hélicoptères C-SAR peuvent recevoir une planche de bord équipé d'écrans de pilotage et de navigation.
Le calculateur de navigation du type NADIR 1000 peut être couplé à un récepteur GPS, une centrale à inertie et un radar doppler.
Le pilote automatique est associé à un coupleur 4 axes numérique assurant les modes SAR (tenue du stationnaire, transition automatique, couplage au calculateur de navigation...).

5.2. Système d'aide à la recherche :

Les équipements suivants sont proposés :

- Radar de recherche 360° (BENDIX 1500),
- FLIR,
- Phare recherche infra-rouge
- Phare de recherche
- PLS (Personal Location System)

5.3. Armement défensif :

L'appareil peut recevoir un armement défensif axial : canon de 20 mm placé en pod, mitrailleuse de 12.7 mm, roquettes de 68 ou 70 mm (2.75'). D'autre part la configuration de la cabine du COUGAR permet de d'équiper l'hélicoptère d'un armement en sabord (mitrailleuse) tout en conservant libre les deux accès latéraux à la cabine grâce à ses larges portes en utilisant les fenêtres de cabine avant qui peuvent recevoir des hublots coulissants. Ceci permet d'assurer la protection de l'hélicoptère pendant les opérations de récupération en terrain hostile.

6. Concept de vol en surcharge/puissance "à la carte"

Sur certaines version du COUGAR C-SAR, Eurocopter a développé un concept d'emploi particulier pour les missions nécessitant une charge utile très élevée en autorisant le décollage de l'hélicoptère en surcharge.

6.1. Vol en surcharge :

Le principe de base utilisé par EUROCOPTER a été d'autoriser une masse au décollage supérieure à la masse normale dans des conditions d'utilisation bien définies afin de limiter les répercussions sur l'endommagement du rotor principal et des autres composants principaux de l'hélicoptère.

La masse supplémentaire décollable en surcharge peut atteindre 15 % dans les conditions suivantes :

- plage de centrage adaptée
- facteur de charge de calcul 2 g
- limitation du domaine de manoeuvre (virage à 30° d'inclinaison)
- limite de VNE (- 10 Kts)
- consignes spécifiques à l'atterrissage.

Le décollage est effectué dans l'effet de sol.

Afin de conserver un niveau de sécurité convenable, il a été défini une procédure de décollage à partir du stationnaire DES 5 ft (1,5 m) permettant à l'hélicoptère de se reposer dans des bonnes conditions de sécurité en cas de panne pendant la phase de décollage. Un taux de montée minimum de 500 ft/mn (2,5 m/s) est assuré après le décollage.

Ces nouvelles conditions d'utilisation ont été élaborées en accord avec les Services Officiels Français (DGA) qui les ont qualifiées pour le COUGAR C-SAR en décembre 1998.

6.2. Puissance "à la carte" :

Le maintien d'un niveau de performances et de sécurité élevé peut nécessiter dans certaines conditions de disposer de niveaux de puissance plus élevés ou de maintenir celle-ci pendant des durées plus longues. Ceci peut être obtenu par l'utilisation d'une structure de régimes moteur militaire dite " puissance à la carte" (en option). Le principe est d'utiliser le moteur à des niveaux de puissance élevées pendant des durées accrues par rapport aux régimes classique moyennant l'enregistrement de l'utilisation réelle des moteurs. Les tableaux ci-dessous donnent la correspondance entre les régimes classiques et les nouveaux régimes militaires.

Utilisation bimoteur (AEO)

Régimes Classiques	Nouveaux Régimes Militaires	Niveau de puissance
	Puissance exceptionnelle bimoteur 15 mn	105 %
Décollage 5 mn	Puissance maxi bimoteur 30 mn	100 % (référence)
Maxi continu : non limité	Maxi continu : non limité	80 %

Utilisation monomoteur (OEI)

Régimes Classiques	Nouveaux Régimes Militaires	Niveau de puissance
OEI 30" (Super Urgence)	Super Urgence 2'	116 %
OEI 2' (Maxi Urgence)	Maxi Urgence 15'	108 %
OEI Continu non limité (Intermédiaire urgence)	Intermédiaire Urgence non limité	100 % (référence)

6.3. Surveillance de l'utilisation :

La sécurité de l'appareil peut être complétée par le système centralisé de surveillance qui permet d'assurer l'enregistrement des dépassements éventuels de limitations, de calculer l'endommagement des moteurs et du système de transmission, de contrôler la puissance du moteur et de surveiller le bon fonctionnement des ensembles dynamiques de l'hélicoptère (surveillance vibratoire).

Associé au vol en surcharge et à la puissance à la carte, les paramètres suivants sont enregistrés :

- dépassement des limitations moteur,
- conditions d'atterrissage.
- régime rotor, couples.

Pour avoir un niveau de sécurité équivalent pour le moteur et le système de transmission, le temps d'utilisation en surcharge est majoré par rapport à l'utilisation normale.

7. Conclusion :

Le COUGAR est un hélicoptère de transport militaire éprouvé qui présente un niveau de performances élevées (charge utile, rayon d'action) et des caractéristiques militaires intéressantes (grande cabine avec de larges accès, haut niveau de protection anti-crash...). Ce sont des caractéristiques essentielles pour la réalisation de mission du type SAR de combat.

Grâce à des développement limités à partir de l'une des versions de base du COUGAR, Eurocopter propose des versions SAR de combat équipées de tous les systèmes nécessaires à la réalisation de ce type de mission et adaptées au besoin de chaque utilisateurs. Il s'agit en particulier des systèmes de recherche (FLIR, radar, navigation autonome ou "satellites"), des systèmes d'auto-protection (canon en pod, mitralleuse en sabord, roquettes...) et des systèmes de contre-mesures (détecteurs d'alerte radar, laser, lance-leurres). L'appareil peut recevoir ainsi les équipements les plus modernes parfaitement adaptés au besoin de chaque client tout en bénéficiant temps de la large expérience opérationnelle acqise par cet hélicoptère. Les versions C-SAR du COUGAR constituent d'excellents exemples de revalorisation d'un hélicoptère existant et de son adaptation à une mission particulièrement exigeante.

SYMPOSIUM (B)

Warfare Automation:

Procedures and Techniques for Unmanned Vehicles

Technical Evaluation Report

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Fairfax, Virginia 22030
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Introduction

The Systems Concepts and Integration Panel (SCIP) Joint symposium on *Advances In Vehicle Systems Concepts and Integration* was held in Ankara, Turkey from 26 to 28 April 1999. Symposium (A) *Aircraft Update Programmes, The Economical Alternative?* is reported separately. Symposium (B) *Warfare Automation Procedures and Techniques for Unmanned Vehicles,* reported on here, was the continuation of a series of symposia initially addressing unmanned tactical air vehicles (UTAs) and more recently broadened to include other forms of unmanned vehicles (UVs).

The potential importance of UTAs to NATO was identified in the Advisory Group for Aerospace Research & Development (AGARD) *Aerospace 2020* report and addressed during two symposia during 1997. Many of the concepts of interest, potential system elements and their performance, and issues associated with the development of UTA capabilities were initially addressed during the earlier symposia. This symposium provided an update on progress in these areas and other forms of UVs.

Specifically, the theme of symposium (B) -

> 'provide state-of-the art summary on technologies used for Unmanned Military Vehicles, their operation, their integration into mission systems and battlefield scenarios as well as acquisition and system operating costs. Theoretical studies forecast cost reductions - "Is this supported by real experience?" Special attention is on joint missions of land/sea/air forces, in areas with highly automated and cooperative infrastructures, and simple and hostile environments as well.'

was addressed in presentations in the keynote addresses, four sessions

- Operational Requirements for Unmanned Vehicles,
- Integration Aspects and Mission Management,
- Platform Management and Critical Technologies,
- System Concepts and Mission Experience,

and the roundtable discussion.

The "summary" and evaluation of symposium (B) below is followed by a discussion of the sessions and identification of some of the key points of the presentations-papers and from roundtable, and audience discussion. Conclusions and recommendations are presented at the end of the paper.

Summary - Overview

The presentations-papers and discussions provided useful updates on UTA efforts, related land and sea vehicle efforts. A number of issues and interests identified in earlier meetings were addressed. The nature and content of the presentations-papers ranged from analytical through development and test experiences to broad concept descriptions.

The first session, chaired by Dr. Eli Zimet, included six presentations addressing operational requirements from several points of view: analytic design of highly autonomous air defense systems; design considerations resulting from analysis of UTA functional requirements by an aircraft manufacturer; UTA needs as seen by a defense system program manager and supplier; unmanned land system functional needs and experiences as seen by a program manager and developer-evaluator.

Several very good discussions of operational requirements were presented during the course of the symposium. Most presentations-papers in the first session and several related presentations-papers focussed on functional requirements and provided a broad basis for system planning. Generally, however, the presentations-papers didn't contain quantitative characterizations of operational requirements and weren't extended to system design requirements. The presentations-papers addressing surveillance-reconnaisance-monitoring needs provided more depth of discussion than those addressing other areas. This may be due to the relatively recent emergence of concepts for using unmanned vehicles for combat, particularly those with a high degree of autonomous operation.

Mr. Ken Helps chaired the second session addressing the technical aspects of some of the key subsystems for unmanned vehicles and how the system elements could be integrated into future combat operations. Six presentations-papers were covered in this session and a seventh presentation-paper was included in the next session. The subjects covered in the papers-presentations ranged from an analytical study of alternative approaches to signal processing for micro inertial sensors to a top-level description of a US Office of Naval Research (ONR) concept for fully autonomous UCAVs. The first four papers of the third session, chaired by Dr. B. Mazzetti, addressed important platform management features and technologies for UTAs. The information they provided should be useful to planners and engineers as examples of the state of the art. The last paper provided a broader picture of an integrated program and a good basis for understanding where more detailed/subsystem developments are to be addressed.

Together, the second and third sessions and some of the papers in the first and fourth sessions provided interesting and useful updates of the state-of-the-art of development of several elements of air, land, sea capabilities. Some papers also provided useful quantitative data and overlapped to the requirements and concepts session. The ONR paper, for example, could have served as a top-level context for the concepts session.

The fourth session, chaired by Mr. James Ramage, included: two presentations on UTA design considerations and system concepts; two presentations-papers on development and demonstration of a surveillance UAV and a surveillance land vehicle; and two updates on the use of surveillance UAVs (CL-289 and Predator).

Together, the presentations-papers addressing system concepts in session IV, related presentations-papers in the earlier sessions, and a keynote address provided interesting pieces of the emerging picture of uses and concepts for unmanned support of combat and non-combat operations. Many of the pieces of the overall picture are, however, still missing or have not yet been clearly identified.

Roundtable participants and audience attendees discussed: operational requirements; levels of autonomy and corresponding time frames; cost considerations; integration with battle management systems and infrastructure; and, which way forward.

Generally, recent experience with the use of UTAs for surveillance and reconnaissance is providing a basis for better understanding of the capabilities and uses/requirements for UTAs and land/seagoing UVs. Ongoing research & development efforts are providing insights into alternative approaches for attaining future capabilities and providing information to support such efforts. Some of the ongoing efforts may also provide a better basis for understanding the economic aspects of integrating UTA capabilities; however, the symposium discussions indicate that the development of cost and cost effectiveness information still needs considerable work. Another area of concern is the largely independent nature of ongoing programs and the need for increased attention to ensuring that the systems of the future can work together in a NATO environment. Emphasis should be given to developing and describing a top-level framework for future efforts, including symposia, working groups, and other forms of information exchange.

Session I: Operational Requirements For Unmanned Vehicles

The first paper of this session, *A Framework for the Automation of Air Defence Systems,* focussed on the automation of short range air defense (shorad) systems, i.e., sensors and sets of kill vehicles, and very short range air defense (vshorad) systems within a distributed architecture. It was concluded that a pool of algorithms would be needed for the air defense tasks. Post-presentation discussion of the aspects of integrating multiple sensor inputs (some from outside the systems) and overall firing control of highly autonomous shorad/vshorad systems will need to be addressed further.

The second paper, *UCAV: Dassault Aviation Point of View,* focussed on the functional aspects of operational requirements, i.e., affordability, lethality, flexibility, availability, survivability and safety and their relation to design considerations such as platform size, weapons, signature, sensor suite, et al., in an integrated architecture. Three critical issues (communications, collision avoidance, package coordination) were addressed and the presentation closed with a discussion of current activities. It was stated in the post-presentation discussion that an overall goal of 30% life cycle cost reduction was being addressed; however, the communications costs being considered were only those associated with the package/UCAV communications, i.e., order of 50 km.

The third paper, *UAV Requirements and Design Considerations,* presented by Maj. Dr. Torun of the Turkish Land Forces Command, also addressed functional requirements in terms of the features and capabilities needed for unmanned air vehicles (UAVs). Several capabilities, e.g., air vehicle radius of action and endurance, ground control station safety and security, payload and datalink design considerations were identified and discussed. One of the key points noted during the presentation and post-presentation discussion was that some payloads, e.g. synthetic aperture radars (SARs), may add significant costs, even exceeding the cost of the aircraft. The level of detail in this paper provided a good complement to the previous paper and the next one which explicitly discussed selected UAV design considerations for operations in Turkey.

The fourth paper, *An Analysis on Operability of Turkish Unmanned Aerial Vehicle Systems Over Turkish Territory,* provided a more explicit discussion of tactical UAV requirements (size, number, speed, range, manning, et al.) and tradeoffs for operations in Turkey. Considerations such as the ability of VTOL and catapult systems to operate from highways and ships rather than being dependent on airfields were discussed as well as the need for a bigger engine for VTOL systems and the potential reduction in range. Although two different types of systems may be needed, a quick response, truck launched UAV system with 50 km range, using two well integrated vehicles (with trailers) which could be transported in existing cargo aircraft, with a crew of 6 or less would fit well with Turkish operational conditions.

The fifth and sixth papers, *UK Requirements for Unmanned Land Vehicle Combat Engineer Support* and *UK Experience With Unmanned Land Vehicles for Combat Engineer Applications* described a broad, multi-year robotic land vehicle (RLV) program aimed at supporting systems in service in the next 10 years. The fifth paper and presentation addressed operational requirements and methods of achieving them through adaption of existing Combat Engineer Vehicles for remote teleoperation. Pertinent tasks for such vehicles include wet and dry gap crossing, obstacle breaching, route maintenance, countermine clearance, construction of obstacles, and blocking of routes. The program's focus has been on development and demonstration of applique kits to provide teleoperation capabilities for normally manned vehicles. The fifth presentation provided a broad description of the efforts. The sixth paper, provided an explicit description of developmental activities. A key element in the efforts, particularly from the standpoint of affordability, was the use of "simple" technology.

Session II: Integration Aspects And Mission Management

The presentation-paper *Signal Processing for Micro Inertial Sensors* addressed alternative approaches to improving the accuracy of such sensors. It was concluded that averaging the outputs of multiple sensors could be used to obtain improved accuracy while keeping computational requirements down. Discussion with the presenter, Dr. Allen Stubberud, suggests that the approach used in the paper may also have other UTA design and operational sensing uses which need to be explored.

Two of the presentations-papers, *Controlling Unmanned Vehicles: The Human Factors Solution* and *An Evaluation of Input Devices and Menue Systems for Remote Workstations,* addressed how human factors could affect operations and workstation use. The quantitative results and operator performance insights regarding datalink bandwidth reduction and workstation design features provided in these presentations-papers should be useful to future system designers. It would be useful to have a central clearinghouse for such information.

The presentation-paper *Advances in UAV Data Links: Analysis of Requirement Evolution and Implication on Future Equipment* presented an analysis of operational and systems requirements and features of a UAV datalink design. This well focussed presentation-paper provided a comprehensive, quantitative characterization of requirements and a potential datalink architecture. The presentation-paper was a good complement to the operational requirements discussion in session I and the discussion of architectural considerations provided a useful basis for addressing integration aspects of other systems.

The presentation-paper *Command and Control System of Unmanned Surface Drones for Seamine Disposal* addressing operational needs and concepts for unmanned control of mine sweeping units was also an interesting complement to the papers on UTAs and to the ones on unmanned land vehicles presented at the end of the previous session. The mine sweeping concept description and operational needs discussion in this presentation-paper helped to fill in another portion of the broad spectrum of potential UV uses and the system features discussion provided an interesting update on the state-of-the art in the area.

The ONR presentation-paper *Distributed Intelligence, Sensing, and Control for Fully Autonomous Agents* provided this session with both a top-level concept for UCAVs and a description of ONR research efforts to support development of the capabilities of interest. A number of advanced information system, airborne system management, and architecture concepts were described in the presentation-paper along with a discussion of specific research activities being undertaken to attain the capabilities. Together, the presentation and paper provide a framework and objective architecture for planning future efforts, identifying issues of interest, and measuring progress in the overall UCAV area. Two issues representative of areas that need to be addressed in future symposia were brought up in discussion of the presentation. The first issue is how to evolve to the autonomous concept in the (far-term) time frame of the concept. The second issue is who will be responsibile for the development and management of the interface to other systems and operations which may also be ongoing.

Session III: Platform Management And Critical Technologies

This session included four presentations addressing developmental, experimental, and operational experience with air vehicles and subsystems. A fifth presentation addressed, at a higher level, the development of UAVs for the German army. The first presentation-paper, *Test and Evaluation of the Man-Machine Interface Between the*

Apache Longbow and an Unmanned Aerial Vehicle, described the results of test and operational personnel using a simulator for an assessment of the man-machine interface aspects of teaming a helicopter with a UAV platform, crew workload, and their effectiveness. It was noted during the post-presentation discussion that the crew didn't fly the UAV, but controlled its flight between way points and controlled the sensor; treating it as another of the inputs available in a combat operation. This presentation-paper was particularly of interest for: the insights and demonstration of how to use/extend current tools to gain design information; the approach to acquiring quantitative data prior to building-testing units; and, the approach to keeping development costs down.

The second and third presentations-papers, *Flight Control Law Design and HIL Simulation of a UAV* and *Unmanned Research Vehicle (URV): Development, Implementation, and Flight Test of a MIMO Digital Flight Control System Designed Using Quantitative Feedback Theorey*, provided examples of recent Turkish and US experience with developing flight control systems. The presentations-papers described experiences with analytical design and extension to hardware in the loop (HIL) simulation approaches for flight control. As examples of design and test experiences, the presentations-papers provided useful updates on process options for future UTA development.

The fourth presentation-paper, *CRESES: A Radar Sensor for Battlefield Surveillance UAVs*, described a SAR/MTI radar sensor for air-to-ground surveillance UAVs and experimental results from a helicopter borne test of the radar. Given the importance of SAR/MTI radar sensing to UTA surveillance and strike missions, this paper provided an interesting update on a critical technology and a comprehensive summary of design considerations.

The final paper of this session. *Unmanned Air Vehicles for the Army - Future Concepts*, provided an up-date on the status and concepts for important German army UAV programs. A review of a current program, the CL-289 which has been in service since 1991, was followed by a discussion of programs for surveillance, jamming and strike missions. A key element in these programs is the development of core technologies and a "system core" for the UTA variants. The evolutionary program activities described in the presentation-paper suggest that significant UTA capabilities may be achievable sooner than would have been expected. Like the ONR paper presented in the previous session, this paper was significant both as a technology update and description of a comprehensive, integrated UTA development program.

Session IV: System Concepts and Mission Experience

The surveillance UAV updates, *Successful Peacekeeping Missions of a UAV, the Drone CL-289 in Bosnia and Kosovo* and *Predator Operations Update*, provided interesting descriptions of these systems and their recent/current use. The discussion included descriptions of real operations, mission capabilities and limitations, and flight performance such as numbers, frequency and flight time. This information plus information on companion systems and near-term improvements to these UAVs was particularly helpful for understanding the state of the art of operational surveillance UTAs.

The presentation-paper *Minature Remote Eye/Ear Land Vehicle* describing the development an experimental real-time video/audio data acquisition platform for live-fire air defense training provided an interesting complement to the earlier (session I) RLV presentations-papers. The approach of using a commercially available radio controlled hobby vehicle and other commercially available equipment, e.g., cameras, as a starting point demonstrated that even non-traditional commercially available equipment can be used to support rapid and economical development of state-of-the art systems. The presentation-paper provided sufficient information to provoke interest in consideration of other, related, types of capabilities. The presentation-paper *Short Range Reconnaisance, The Luna Experimental UAV Program* also addressed the rapid (18 month) development of a easily operated and supported reconnaisance system making as much use of off-the-shelf equipment as possible. The modest cost, powered sailplane like, Luna represents an interesting cost point for the state-of-the art in the tactical systems portion of the UTA spectrum.

The last two presentations of this session, *Design Considerations for Hypersonic UAVs* and *UAV Concepts for CAS* (close air support) addressed the development of higher capability UTAs and their use. Both presentations provided details of the features and performance needed for combat operations. As such, they were a useful complement to the ONR concept addressed during session II and the German army UAV program description in session III.

Roundtable

Five sub-topics, within the broad topic of Unmanned Vehicles from Teleguidance to Full autonomy, were suggested by Professor Dr. Heinz Winter for the roundtable discussion:

- Operational requirements for unmanned vehicles;
- Levels of autonomy and corresponding time frames;
- Relations between cost, level of autonomy, type of mission, etc.;
- Level of integration into the battle management system;
- Which way forward (?).

Several important points were made by roundtable participants and audience members. With regard to requirements, it was noted that progress can be made (even without formal requirements) by considering broad capability needs, e.g., timely coverage, operating in a variety of conditions, etc. The need for consideration of interoperability-compatibility for NATO operations was emphasized by several participants. It was pointed out that just having standards may not be sufficient, working groups and other coordination mechanisms may be necessary.

Concern was expressed regarding the point that although the cost/cost effectiveness aspects of using unmanned vehicles is important, there is as yet little cost information available for either the systems or the infrastructure to support them.

It was pointed out by Dr. Zimet that we have some teleguided systems and some "fire and forget" weapons (e.g., Tomahawk) today and we are moving toward more revolutionary capabilities. We can proceed in evolutionary steps, i.e., including incremental development and commonality of systems for multiple missions as noted by Mr. Helps and Dr. Torun. Dr. Mazzetti and Mr. Ramage noted that we need to address new requirements associated with transitioning from using UVs for ISR to developing capabilities for combat operations. This raises the level of sophistication-autonomy of systems. It is also important to anticipate that not all elements of a system may be working in battlefield situations and consideration needs to be given to this in designing for autonomous operations vs. designing for variable/ adaptive degrees of autonomy.

It was pointed out by Dr. Winter that one way of proceeding in the future is to organize activities with an overview and issues discussion (like in the roundtable) and also focus on science and technology questions.

Conclusions

With the exception of obtaining cost information updates, the theme of the symposium was addressed in a number of interesting and complementary presentations-papers. Unfortunately, it appeared from these presentations-papers that many recent and on-going efforts are highly focussed on the perceived needs of individual nations and organizations. The concepts and systems described at the symposium were only spoken of in a NATO context on a few occasions and in one presentation-paper it was noted that a system would not be interoperable with other NATO capabilities.

An effort is needed to develop a conceptual and decision framework for future development activities. Desirably, it would build on and across various national efforts and include some form of integrated plan for achieving NATO capabilities. Many of the interesting integration, mission and platform management, and critical technologies discussions at this symposium, earlier symposia, and the planned fall symposium could be related to such a framework. Considerations such as how to use unmanned capabilities for broader sets of missions and fit them into broader architectures of C3I capabilities need to be addressed in such a framework.

Support for developing such a framework could be provided by focussing portions of future symposia on continuing issues such as cost-effectiveness and the degree, speed, feasibility, and process for moving to highly autonomous system capabilities.

Recommendations

In the near-term, it would be useful if program and session chairmen could reorder presentations and provide more introductory symposium/session remarks to enhance the understanding of the relation and content of the presentations to come. SCIP members responsible for planning future symposia should give consideration to Dr. Winter's suggestion of how sessions and presentations-papers could be structured and to furthering the development and implementation of a framework such as discussed in the conclusions section above.

A Framework for the Automation of Air Defence Systems*

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Abstract

The need for more efficiency in military organizations is growing. It is expected that a significant increase in efficiency can be obtained by an integration of communication and information technology. This integration may result in (sub)systems that are fully automated, i.e., systems that are unmanned, including unmanned vehicles. In this paper, we focus on the automation of air defence systems, in which integration of communication and information technology is a major issue. We propose an architecture, in which each weapon system has the capability to control itself, whilst acting in a co-ordinated manner with other systems. To realise this task, a weapon system is exactly informed about the activities of all other weapon systems. In our architecture, the role of the men is reduced to the supervision of weapon systems.

1 Introduction

While communication technology is an integral part of military systems, the potentials of information technology have recently been recognized by military organizations. Since it has been demonstrated that information technology provides the possibility to facilitate or to automate a wide variety of tasks that are currently performed by military experts, military organizations are rapidly adopting this technology. Exploiting information technology may lead to a decrease in the number of military personnel required for such tasks, and to an increase of the efficiency in military organizations. In [5, 6], the need for more efficiency in military organizations has been discussed. It is expected that a further increase in efficiency can be obtained by the integration of communication and information technology. This integration may result in (sub)systems that are fully automated, i.e., systems that are unmanned, including unmanned vehicles.

We are interested in the application of information and communication technology and in the impact of these technologies on air defence systems. An air defence system has as goal the defence of a predefined space against physical attack and espionage from the air. To realise this task, air defence systems are equipped with a wide variety of means, such as men, weapons, vehicles, sensors, etc. On the basis of the size of the space that should be defended, NATO distinguishes four categories of air defence systems namely, very short range air defence systems (vshorad), short range air defence systems (shorad), medium range air defence systems, and air defence fighters. Very short range air defence systems defend spaces that range up to 6 kilometres in a horizontal direction and up to 3 kilometres in a vertical direction. For short range air defence systems these sizes are 12 and 6 kilometres in horizontal and vertical direction respectively. For longer distances the remaining categories are used.

In this paper, we focus on the automation of vshorad and shorad systems. Apart from military experts, these systems basically consist of a set of sensors and a set of kill vehicles, which may be located on geographically different bases. Sensors are used to detect incoming targets and to track these targets. Kill vehicles are assigned to destroy targets. A combination of sensors and kill vehicles is called a weapon system, and a shorad/vshorad system can be regarded as a set of weapon systems that are controlled by military experts. Each weapon system is dedicated to the defence of a part of the space assigned to a vshorad/shorad system.

We propose an architecture, referred to as *distributed* architecture, in which each weapon system has the capability to control itself in a co-ordinated manner. This architecture is based on two principles. First, each weapon system has access to the same set of data and the same capabilities to process this data. Second, each weapon[1] and sensor knows the strategies that are used to deploy sensors to observe an area, i.e., a part of the airspace, and to allocate weapons to targets. For example, strategies for sensor deployment and weapon allocation may be that an area is

*This research has been performed within the scope of the NATO SHORAD/VSHORAD Feasibility Study in the Matra BAe Dynamics consortium.

[1] In the following, the terms weapon and kill vehicle are used interchangeably.

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

observed by the closest located sensor and a target is attacked by the closest located weapons, respectively. These principles have as consequence that each sensor or weapon may know exactly what all other sensors and weapons are doing in the system, and can act in a co-ordinated manner. In our architecture, the role of the men is reduced to the supervision and maintenance of the system.

The distributed architecture is only viable if the technology to handle the two principles is sufficiently mature, and we believe that this is the case. To handle the first aspect of the first principle, that is, to provide each weapon system the access to the same set of data, we propose a network to which all entities, including other sensors and weapons, are connected. Each sensor/weapon or other connected entity is able to extract data from the net, and is able to request net capacity (bandwidth/time slots) in order to put data on the net. The acceptance of the request and the capacity that will be allocated to an entity depends on the load of the network and on the importance of the data for other entities. So, dynamic allocation of net capacity is the proposed solution.

To handle the second aspect of the first principle, that is, to provide processing capabilities to each weapon system, the architecture should be equipped with algorithms to perform the tasks that are required for (very) short range air defence, such as data fusion, threat evaluation, weapon allocation, etc. In the literature, a wide variety of potential algorithms has been reported to perform these tasks, see [2, 3, 6, 9]. We propose a framework in which many of these algorithms can be captured. In this framework, we distinguish a pool of algorithmic skeletons and a pool of logical operators. An algorithmic skeleton consists of important control statements. By combining operators and algorithmic skeletons, an algorithm can be generated for a specific task.

It is clear that the second principle, i.e., each weapon system knows the strategies for sensor deployment and weapon allocation, can be handled with above-mentioned techniques as well.

The main advantages of our architecture are performance and reliability. Performance is achieved by the fact that a weapon system has its own processing capabilities and the possibility to load and organize data in an efficient way. Note, that a bad organization of data may lead to a poor performance of an overall system [1]. Reliability is achieved by the fact that each weapon system is informed about each other's activities, which avoids situations that a target is overkilled, or, even worse, that a target is not attacked at all. Other nice properties of the architecture are that it supports modularity and graceful degradation. We note that these latter two properties are also inherent to an autonomous architecture. The main difference between our architecture and systems based on an autonomous architecture, such as the US FAAD system, is that in the latter architecture weapon systems are not informed about each other's activities.

The remainder of this paper is organized as follows: in Section 2, we discuss the distributed architecture in more detail. Since communication and processing algorithms play a major role in this architecture, the two consecutive sections 3 and 4 are devoted to them. Finally, the paper is concluded in Section 5.

2 Distributed Architecture

Our framework to automate air defence systems is based on the concept that each weapon system has the capability to control itself in a coordinated manner. Therefore, we propose an architecture in which all entities are connected to a network. As soon as an entity obtains new information/data, it puts it on the network. All other entities have the possibility to access this information/data. In order to realize that entities act in a coordinated manner, all entities have the same processing algorithms. So, processing of the same data will result in the same results at each entity, given instantaneous differences due to time delays.

The entities that are distinguished for the time-being are weapon systems and command centres. The basic architecture is depicted in Figure 1.

A weapon system consists of a set of kill vehicles and a set of sensors. Communication between kill vehicles and/or sensors is realised through the network. Typical information that will be put on the net by kill vehicles are plans to attack a target. Sensors will put measurements performed in the real world on the network.

A command centre is hierarchically organised, consisting of three levels. A battalion at the highest level controls a set of batteries, and a battery in its turn controls a set of platoons. Each level is connected to the network. So, information from the battalion destinated for a battery can also be obtained by a platoon. Although each entity in a specific level has all available information and processing capabilities to take justified decisions, the reason to preserve the hierarchical organization in command centres is that a higher level echelon should have the possibility to overrule a decision at a lower level echelon.

The different levels in a command centre are distinguished by the functions that are performed at each level. While the tasks to be performed at higher levels are strategical in character, at lower levels the tasks are more tactical. For example, a battalion is also connected with external systems and it may receive recognised air picture data from these systems. It is the responsibility of the battalion to select and distribute proper data to all entities through the network. At platoon level, weapons are commanded to attack a target.

The major advantages of distributing data to all entities through a network are reliability and performance. Reliability is achieved by the fact that each entity is informed about the activities of all other en-

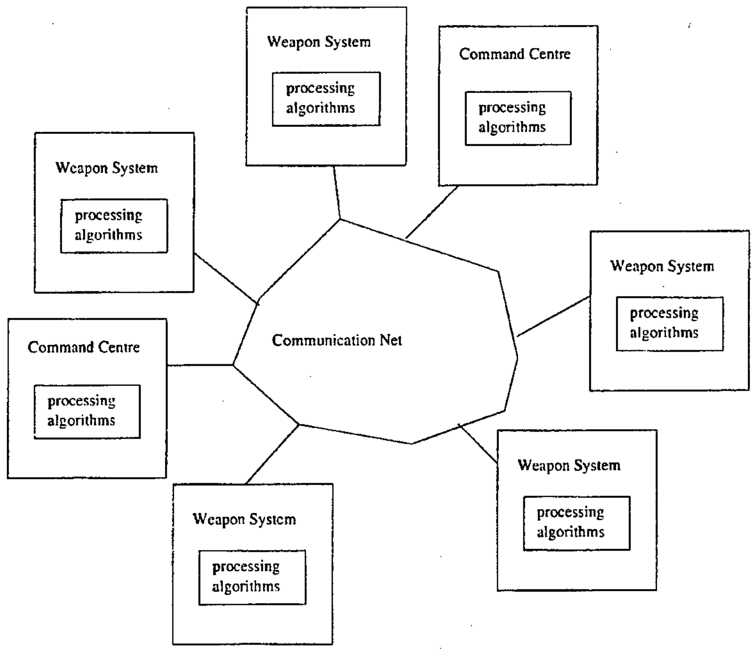

Figure 1: Basic architecture

tities and that each entity is capable to obtain and process data. By informing entities about their activities, situations of over-kill or not engaging a target can be avoided. For example, suppose that w_1 is the most obvious weapon to engage a target, but is unable to fulfil this task for some reason. Since the second obvious weapon, let's say w_2, can observe that w_1 is not going to engage the target, w_2 knows that it should engage the target.

By providing each entity processing capability, entities become independent of each other. So, they do not suffer from entities that fail to perform processing tasks. Let us consider the following situation for track correlation. Suppose that only one entity is able to perform track correlation and is also responsible for putting updated tracks on the network. If this entity fails to perform this task, then the entities have an obsolete track. Furthermore, the measurements provided by sensors in this case can be considered as a waste of effort. Another advantage of providing processing capability to each entity is that even if an entity fails to process some data, it still can obtain the results of processing, since other entities have processed the data, and may put it on the net.

Performance is achieved by the fact that there is a minimum delay in obtaining data, since all data is freely available. Since each entity has its own processing facilities, the queues for processing an amount of data will be much shorter compared to the situation, in which there would be one processing unit and each entity was assigned to this unit. Furthermore, processing algorithms may be tuned towards the tasks that should be performed by an entity, e.g., by incorporating specific domain knowledge in the algorithms. An additional advantage of providing each entity processing facilities is that graceful degradation is supported. This means that if some entities are completely destroyed, the other entities can still perform their tasks.

Since an enormous amount of data may flow through the network, congestion of the network is an obvious possibility in this architecture. In the next section, we describe a method to prevent and to cope with congestion.

3 Communication

In the proposed architecture (Figure 1), relevant data need to be shared between entities in an "all know everything" setup. Therefore data generated by one entity (e.g. relating to the detection of air targets by a sensor) should be available nearly instantaneously throughout the system, e.g., for track correlation, multi-sensor data fusion, threat evaluation, etc. This obviously calls for high-capacity data transmission between the system's elements. However, in multi-element wireless communication, capacity usually is limited.

A military network's data throughput capacity is embodied in time slots and frequencies/bandwidths embedded in a cyclic framework. A well-known representation (derived from the system Link-16 protocols) is shown in Figure 2. At the setup of such a (secure) communications network, each element is allotted an appropriate number of slots within the cycle in which it may transmit, at the prescribed hopping frequencies. In practice, this method leads to non-optimal usage of network capacity, as slots are allotted to sys-

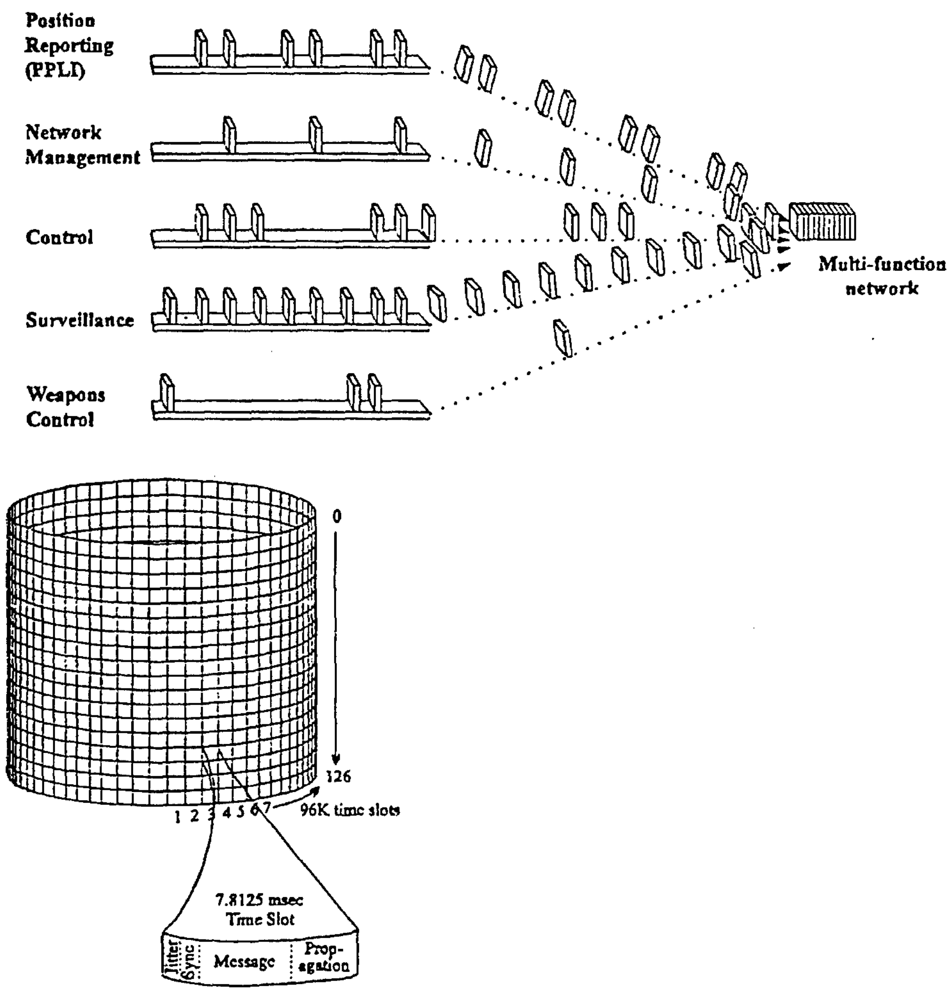

Figure 2: Cyclic representation of frequency bands vs. time slots

tem elements regardless of the volume of data generated and also regardless of the relevance of such data to the task. E.g., sensors having nothing of interest to report still consume part of the communications capacity.

In a typical air assault scenario, some entities (e.g. the upfront sensors) may generate lots of relevant data as they "see" many new targets. Such information may consist of track data as well as of signature characteristics. If the number of transmission slots originally allotted to those sensors is insufficient for transmission of all of the relevant information, optimal application of network capacity requires allocation of extra resources for the timely dispersion of such data.

A method of optimizing transmission capacity in a distributed network is proposed here. It is called the dynamic allocation of slots, frequencies and bandwidths. In this method, each system element requiring to transmit extra data first submits a transmission request comprising a weighted assessment of the urgency of its data. Since in the proposed architecture knowledge is dispersed throughout the system and entities possess the intelligence to decide whether the information they generate merits putting it on the net, the assessment of urgency can be made. Typical parameters that play a role in such an assessment are new target recognition results, optimum kill probability, time left to last launch opportunity, value of the threatened asset, etcetera. The extra slots (frequencies, bandwidths) are allocated dynamically, through a distributed management function and in proportion to the "weights" of the current requests. This approach is thought to be feasible, since successful time sharing schemes for mainframe computer operating systems are based on a similar concept. We further believe the method is promising, as it may generate a more efficient application of a scarce commodity.

We note that the proposed method should be complementary applied to (existing) data compressing techniques. It has been proven that data compressing techniques may considerably reduce a piece of data that should be transmitted. Once the transmitted data has been received, it may be decompressed such that the semantic of the original data is preserved.

4 Processing algorithms

In Figure 1, it is depicted that processing algorithms are required by weapon systems as well as by command centres. Within a command centre algorithms are required at all levels for various tasks. Typical tasks that may be performed by algorithms are track filtering and correlation (in order to produce air pictures), identification, threat evaluation, weapon allocation, etc. While some of these tasks should be performed by most entities and at each level, other tasks are performed just at some levels within a command centre. For example, an air picture is built up by all entities and on each level. Therefore, all entities and all levels should be equipped with track filtering, correlation, and data fusion algorithms. Intelligence gathering is a task that will typically be performed at battery and/or battalion level. So algorithms that support this task should be installed at these levels.

Many algorithms reported in the literature can be used to perform a wide range of tasks required for air defence systems. As an example, let us consider the task of track filtering and potentially useful algorithms for this task that can be found in text books. The core of track filtering is deciding whether a point is within or outside a polygon. Track filtering provides the possibility to remove air tracks that are outside a geographical area of interest.

Possible solutions for track filtering might be based on, e.g., point inclusive algorithms or nearest neighbour algorithms. The idea behind point inclusive algorithms is to draw a vertical or horizontal line from a point to the polygon, while counting the number of intersections between the line and the polygon. An even number of intersections implies that the point is outside the polygon, while an odd number implies that the point is inside the polygon. Intersections that are also a point of contact are counted as two intersections. The idea behind nearest neighbour algorithms is to assign a point to the most likely polygon. Therefore, these algorithms compute for all (relevant) polygons the probability that a point is within a polygon.

What algorithm to select for a task depends on the characteristics of the task and the available input. In general, each algorithm will have its own strong and weak points. For example, a point inclusive algorithm may be very fast, but on the other hand, it requires a detailed geometrical description of the polygon.

In the next section, we propose a framework that captures a wide variety of algorithms that may be used for several tasks by air defence systems.

4.1 Framework

Our main goal is to develop and implement algorithms that may be used for several air defence tasks. It has been widely recognised that the development of software for complex systems is a tough process. Therefore, several methodologies have been developed to facilitate this task at various levels, ranging from the design to the implementation. For example, data-driven, object-oriented, and top-down functional methodologies are well known at the design level, and for programming purposes the top-down and bottom-up methodologies are well known. Depending on the nature of an application, software engineers choose a number of these methodologies to develop software. For the software development of the proposed air defence system architecture, we will not design software from scratch but attempt to tailor existing algorithms for various functions. In general, the pseudo-code of these algorithms can be found in textbooks. Tailoring an algorithm to a function boils down to, e.g.,

- Verifying whether the assumptions on which an algorithm is based are realistic for the function or not, e.g., is the input expected by the algorithm available?

- What is the best way to represent the input for the algorithm? The representation should be such that it fits the problem domain, i.e., the problem that should be solved by the function.

- Are all operators in the algorithm meaningful? If not, should they be modified, or deleted?

- Are the control statements in the algorithm meaningful or should they be modified, or deleted?

- How should the output be represented?

We note that performing the above-mentioned tasks successfully requires advanced skills of a software engineer.

On the one hand, we have observed that several (textbook) algorithms might be used for a specific air defence task, while on the other hand an algorithm might be used for several air defence tasks. For example, a point inclusive algorithm as well as a nearest neighbour algorithm can be used for track filtering, while the latter algorithm can also be used for identification and threat evaluation. Our goal is to come up with a set of algorithms such that a single algorithm might be used for several air defence systems tasks on the one hand and on the other hand, we prefer to have several algorithms available to perform a task. To realise this goal, we suggest to implement a set of algorithmic skeletons and a set of operators. In an algorithmic skeleton, important control statements are implemented and operators are implemented in an abstract way. In a separate pool, operators are implemented in more detail. An operator describes how objects should be represented and what its impact will be on each object. Once these two sets are available, a user may construct its own algorithms by combining skeletons and operators. In this way, we re-use software as much as possible.

We note that for many textbook algorithms the distinction between algorithmic skeletons and operators can easily be made. Observe that an algorithm can be regarded as an ordered list of control statements and operations.

Once an algorithm has been constructed by combining operators with an algorithmic skeleton, this algorithm has to be instantiated. This means that values for the input parameters should be made available to the algorithm. Then, the algorithm can be compiled and executed. In Figure 3, the whole process is depicted.

The main advantage of our framework is that there are several alternative algorithms to perform a task, each with its own strong and weak points. If the result of an algorithm is unsatisfactory, one may assemble another algorithm.

4.2 An example

In this section, we illustrate our framework by means of a simplified identification algorithm. Identification algorithms collect data/evidences from multiple sources and combine these data in order to produce a composite identification of an object. Potential sources of data include recognised air pictures, procedural indicators (e.g., restricted area violations), acoustic sources, etc.

In our example, the goal is to determine what objects are in the airspace on the basis of a sequence of independent evidences. To solve this problem, we will discuss two techniques that might be used namely, one emanated from probability theory [7] and the other emanated from Dempster-Shafer theory [8]. Both theories provide us a tool to combine several bodies of evidence. For the similarities and differences between these theories, we refer to [4]. In the following, we will stress the combination of evidences.

In the airspace, we want to distinguish between civil aircraft, military aircraft, and birds. The set $D = \{\textit{civil aircraft, military aircraft, bird}\}$ is called the frame of discernment. As time went on, evidences will be collected that support or reject a subset of D.

Let $D' \subseteq D$, and $P(D'|e_n)$ be the probability in D' given a sequence of $e_1, e_2, e_3, ..., e_n$ evidences. To update the probability in D', whenever a new body of evidence e becomes available, the following formulae can be used according to probability theory.

$$P(D'|e_n, e) = P(D'|e_n)\frac{P(e|D')}{P(e)}$$

and

$$P(D'|e_1) = \frac{P(e_1|D')P(D')}{P(e_1)}$$

Note that in the formula above we assumed that evidences are independent of each other.

Before introducing the rule to combine evidences according to the Dempster-Shafer theory, we introduce the notion of basic probability assignment. A basic probability assignment to a set D', $m(D')$ can be regarded as the measure of belief that is exactly committed to D'. A basic probability assignment should satisfy the following properties $m(\emptyset) = 0$ and $\sum_{D' \subseteq D} m(D') = 1$.

Let $m_{e_n}(.)$ be the basic probability assignment induced by a sequence of evidences $e_1, e_2, e_3, ..., e_n$. To update the belief in a set D', whenever a new body of evidence e becomes available the following formula can be used.

$$m_{e_n} \oplus m_e(D') = K^{-1} \sum_{\substack{i,j \\ D_i \cap D_j = D'}} m_{e_n}(D_i) m_e(D_j)$$

in which D' is a non empty set, $D_i, D_j \subseteq D$, and

$$K = \sum_{\substack{i,j \\ D_i \cap D_j \neq \emptyset}} m_{e_n}(D_i) m_e(D_j)$$

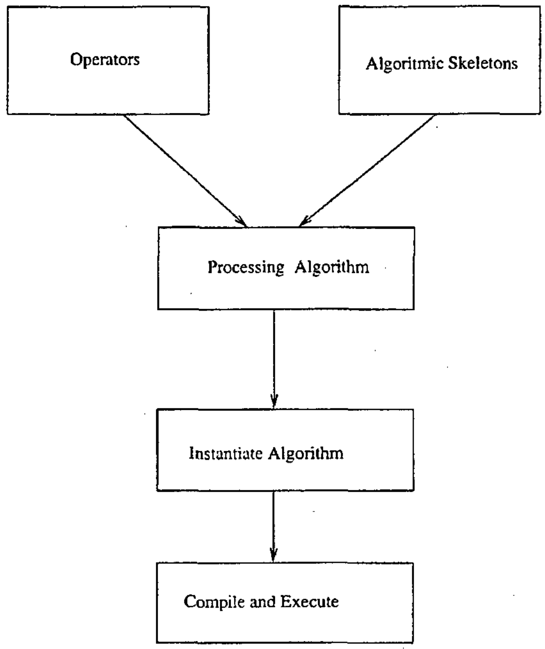

Figure 3: Framework to capture algorithms

We note that K is a normalization constant and is required to meet the property $m(\emptyset) = 0$.

Each of the above mentioned techniques can be implemented as a separate combination operator. Let our pool of operators consists of Combine_Prob, which is based on probability theory and Combine_DS, which is based on Dempster-Shafer theory.

Assume that the following algorithmic skeleton is available, in which a Combine operator appears.

```
Program Skeleton(D, Var Concl);
Get(e); /* Get reads a body of evidence /*
first_evidence := 'true';
while e ≠ '' do
    j:= 0;
    while j < 2^D do
        Combine(D'[j], first_evidence, e, Concl);
            /* Combine updates the belief/
               likelihood in D'[j] /*
        j:= j+1;
    od;
    Get(e);
    if first_evidence = 'true'
    then first_evidence := 'false';
od;
end.
```

This skeleton requires as input a frame of discernment D, e.g., $D = \{$*civil aircraft, military aircraft, bird*$\}$. The output, referred to as *Conclusion*, will be subset(s) of D to which a measure is attached expressing the belief/likelihood that an object can be identified which one of the elements in the subset(s). As long as evidences are available, the belief/likelihood in each subset $D' \subseteq D$ is updated by the skeleton. Suppose that the a priori probabilities $P(e)$ and the a posteriori probabilities $P(e|D')$, in which $D' \in \{$*civil aircraft, military aircraft, bird*$\}$ and the goal is to identify whether an object is a bird, a civil or a military aircraft. Then, the above mentioned skeleton together with the Combine_DS operator can be used for this purpose. Now the identification program will be

```
Program Identification(D, Var Concl);
Get(e);
first_evidence := 'true';
while e ≠ '' do
    j:= 0;
    while j < 2^D do
        Combine_Prob(D'[j], first_evidence, e, Concl);
        j:= j+1;
    od;
    Get(e);
    if first_evidence = 'true'
    then first_evidence := 'false';
od;
end.
```

Once we have specified the input values, i.e., D, the required probabilities, the program is instantiated and ready for execution.

We note that if both probabilities $P(e)$ and $P(e|D')$ are not available, we have the possibility to build in the Combine_DS into the skeleton, resulting in an alternative identification program.

Suppose that our pool of operators contains a combination operator that is able to combine images, i.e., a body of evidence results in an image of an environment and we are able to combine different images, the same skeleton may be used for threat evaluation.

Summarising, we propose a framework that consists of a pool of operators and a pool of algorithmic skeletons. An operator manipulates a number of objects according to a certain technique. An algorithmic skeleton consists of control statements and abstractly defined operators. Now, an algorithm may be constructed by combining skeletons with operators. In this way, operators and skeletons can be used for several air defence tasks, and several alternatives will be available for a single air defence task.

5 Conclusions & further research

We have discussed a framework for the the automation of air defence systems. In this framework, the integration of information and communication technology is a major issue. We have proposed a distributed architecture, in which each weapon system has the capability to control itself in a co-ordinated manner. In this architecture, a weapon system is exactly informed about the activities of all other weapon systems. We have touched on how our architecture can be implemented using information and communication technology. Communication between entities and adequate processing of data by each entity are of vital importance. Communication between entitities is realised through a communication net, and net capacity is dynamically allocated to entities. For the processing of data, we have proposed to implement a wide variety of algorithmic skeletons and operators. An algorithm to perform an air defence task may be constructed by combining algorithmic skeletons and operators.

Furthermore, we have discussed the advantages of our architecture in relation with other architectures.

Topics for further research are the implementation and evaluation of the architecture.

Acknowledgement Dr. Hein Veenhof of NLR is thanked for his valuable comments on earlier drafts of this paper.

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REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	10 May 1999	Conference Proceedings

4. TITLE AND SUBTITLE

The Unmanned combat Aircraft (UCAV): the point of view of an aircraft manufacturer

5. FUNDING NUMBERS

F61775-99-WF007

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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FRANCE

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES

EOARD
PSC 802 Box 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

CSP 99-5007

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

ABSTRACT (Maximum 200 words)

There is an increasing interest to develop an unmanned plane. It is possible to consider innovator concepts of unmanned combat planes, which is a technically possible solution. Since 1989, at the end of the cold war there is an operational plan characterized by: peace operations maintenance; theater diversities; multiple periods of deployment; joint deployment operations trying to secure peace; the on the level of losses/ effects on the civil populations; and minimization of prisoners.

14. SUBJECT TERMS

EOARD, aircraft, unmanned

15. NUMBER OF PAGES

N/A

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

LES AVIONS DE COMBAT NON HABITES (UCAV)
Le point de vue d'un avionneur

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RESUME
Après avoir situé le contexte dans lequel un intérêt croissant a pu se dégager pour promouvoir le développement des avions sans pilote à bord, l'article, dans un premier temps, montre comment, après une première étape consacrée à déporter l'opérateur pour s'affranchir de ses limites propres (telles que endurance)- étape qui se matérialise d'ores et déjà par des systèmes au stade de la démonstration ou opérationnels- il est possible d'envisager des concepts novateurs d'avions de combat non habités intégrés dans des dispositifs complexes qui répondront aux critères des utilisateurs (coûts, létalité, flexibilité, disponibilité, attrition).
Dans un second temps, sur la base des travaux réalisés sur ce thème par Dassault Aviation, l'article s'applique à recenser les techniques et technologies jugées nécessaires à la mise en œuvre de ces dispositifs perception, contrôle, interactions homme système,...

1. INTRODUCTION

Depuis 1989, la fin de la guerre froide a provoqué l'émergence de nouveaux scénarios de crise ; ceux-ci sur le plan opérationnel se caractérisent par :

- des opérations de type maintien de la paix
- des théâtres diversifiés et multiples,
- des périodes de déploiement longues,
- des opérations conjointes,
- des opérations type temps de paix contraignantes au niveau des pertes et des effets collatéraux sur les populations civiles et la minimisation des prisonniers (pour son impact médiatique).

A côté de ces aspects à caractère opérationnel, les restrictions budgétaires que ces changements ont engendrées ont accentué les besoins pour des systèmes comparativement moins chers. Un certain nombre de concepts sont en train d'émerger pour diminuer de manière radicale leurs coûts, ceux-ci étant maîtrisés au travers d'une approche globale prenant en compte les coûts de développement, de production et d'utilisation et de soutien.

Enfin de nouvelles technologies arrivent à maturité, souvent en provenance du monde commercial et civil, et deviennent disponibles pour des applications militaires ; par exemple les communications, les capteurs, l'informatique avancée,...

Partant de ces constats, les Avions Sans pilote (ASP) sont des solutions techniquement envisageables pouvant prétendre répondre à ces différentes exigences par leur coût réduit, qu'il soit d'acquisition (diminution de la complexité) ou d'utilisation (capacité de réutilisation, nouveaux concepts de formation et d'entraînement des opérateurs), leur flexibilité opérationnelle et la diminution des contraintes de conception que permet d'envisager l'absence d'équipage à bord de la plate-forme.

2. LE PASSAGE AUX PLATES-FORMES NON HABITEES

2.1. Place de l'opérateur humain

Associés aux nouvelles technologies qui permettent d'en envisager la faisabilité, de nombreux éléments orientent la tendance en faveur des véhicules non habités :

- Eloigner l'homme du danger,
- S'affranchir des limites de l'opérateur humain telles que l'endurance ou les limites physiologiques,
- Relâcher les besoins pour un entraînement continu et approfondi, même en temps de paix,
- Permettre le relâchement des contraintes de conception des plates-formes.

Cependant l'élimination totale de l'intervention de l'homme semble aujourd'hui et sans doute pour longtemps encore une utopie du fait des apports que ce dernier peut amener à un système (essentiellement au travers de ses capacités cognitives) :

- Perception et évaluation de la situation au travers de l'expérience accumulée,
- Son adaptabilité à de nouveaux contextes opérationnels,
- La prise de décision,

mais aussi parce qu'il est un élément de faisabilité, de simplification ou d'adaptabilité que les technologies les plus sophistiquées ne savent pas encore satisfaire à ce jour.

2.2. Intérêt technique des ASP (Avions Sans Pilote)

La prise en compte des contraintes liées à la présence de l'homme à bord influence fortement la conception et les performances du système aérien.

De nombreuses pénalités en terme de coût et masse sont associées à des systèmes requis uniquement ou

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

principalement par la présence de l'équipage et comprennent en particulier les commandes et visualisations, le siège éjectable, la combinaison anti-g, la génération d'oxygène, la pressurisation et d'autres moyens de contrôle de l'environnement cabine, ainsi que la prise en compte de la vulnérabilité.
Les capacités et les types de manœuvre de l'avion sont bornées par les limites physiologiques telles que la tolérance au facteur de charge, la susceptibilité à la désorientation spatiale, voire les problèmes d'endurance et de fatigue.
Avec l'homme à bord tous les aspects de la conception de l'avion sont fortement orientés. La taille de l'avion, ses formes et son architecture générale sont affectées . Ainsi le positionnement du cockpit à l'avant résultant des besoins en visibilité directe impose des formes et des matériaux qui se répercutent sur la traînée .
Par ailleurs force est de constater qu'en grande partie, la vie opérationnelle des avions de combat actuels est consacrée à l'entraînement et au maintien en condition opérationnelle des équipages, ce qui nécessite des durées de vie en conception bien supérieures au strict besoin qui serait induit par les seules opérations réelles.

3. QUELS OBJECTIFS ?

Il convient ici de situer ces systèmes vis à vis de leurs apports potentiels pour leurs futurs utilisateurs en se référant à des critères si possible quantifiables soit absolus soit relatifs (en comparaison à des systèmes existants). Les critères les plus communément utilisés pour évaluer des systèmes opérationnels sont les suivants : .

- Coûts,
- Létalité,
- Flexibilité,
- Disponibilité,
- Attrition (Survivabilité et Sécurité).

3.1. Coûts

Comme déjà évoqué le coût des systèmes est une préoccupation majeure des utilisateurs. Ce coût se doit de recouvrir tous les aspects économiques relatifs à un système intégrant son développement, son acquisition et son utilisation. L'objectif recherché est d'arriver à un coût d'acquisition et de possession très inférieur à celui d'un système piloté. Le nombre d'heures de vol nécessaire à l'entraînement des opérateurs pourra diminuer grâce à la simulation et à un emploi plus occasionnel.

3.2. Létalité

Les avions d'attaque sans pilote devront être capables d'emporter un nombre significatif de petits armements intelligents qui devront compenser leur petite taille (faible charge militaire) par une plus grande précision. Chacun devra emporter l'armement et son capteur associé pour assurer une seule mission correspondant à l'attaque d'un objectif très spécifique.

3.3. Flexibilité

Les avions sans pilotes devront répondre pour leur mise en œuvre aux objectifs suivants :

- Un système de support et de soutien le plus léger possible,
- Une modularité permettant des changements de configuration,
- Une petite taille pour faciliter un transport aéroporté.

3.4. Disponibilité

Le taux moyen de pannes des équipements doit être le plus faible possible pour une meilleure fiabilité opérationnelle et donc une plus grande robustesse aux défaillances. La notion d'emploi occasionnel permet d'envisager des phases de stockage et donc le recours à des nouveaux types de maintenance à l'échelon industriel.

3.5. Attrition

L'absence d'équipage permet d'exposer ces avions sans pilote à plus de risques et conduit à envisager plus facilement leur perte. De ce fait, ils s'inscriront dans une logique d'attrition maîtrisée en fonction des conditions d'emploi opérationnel et de leurs coûts associés.

3.6. Quelles perspectives pour les systèmes aériens non habités ?

Il est vraisemblable que la transition qui se dessine au travers de systèmes de reconnaissance tactiques (aujourd'hui en service ou en expérimentation) et par des programmes de démonstration technologiques (aux Etats-Unis en particulier), se déroulera selon les deux étapes suivantes.

3.7. Première étape : les Avions de Reconnaissance Sans Pilote (ARSP)

Dans cette première étape, il s'agit d'éliminer la présence de l'homme à bord de la plate-forme lorsque celle-ci ne se justifie qu'autour de motivations techniques pour la réalisation des missions (mise en œuvre plate-forme, mise en œuvre capteurs), sans qu'il soit cependant un élément clé de la gestion en temps réel de leur déroulement (hors raisons techniques).

Les principales missions entrant dans cette catégorie sont la reconnaissance quasi temps réel qui permet de collecter, traiter et diffuser le renseignement dans pratiquement toutes les formes de conflit ; elles couvrent une gamme de mission pouvant aller de la mission de détection aérienne avancée (AEW), le relais de communication, les missions de type écoute (SIGINT, COMINT, ELINT,... jusqu'à la collecte d'image-IMINT), dont l'importance est cruciale pour les types de conflits et d'opérations considérés.
Les missions à caractère offensif telles que l'escorte électronique, pourraient également s'avérer du ressort

de ces types de systèmes bien que se pose alors le problème de cohérence entre escorte et escortés.
Les plates-formes correspondantes rentrent en général dans des catégories dites HALE/MALE (Haute/Moyenne Altitude Longue Endurance) et présentent des caractéristiques globales similaires avec leurs équivalents habités (grand allongement, faible manœuvrabilité, Radôme/IRdômes et volumes de soutes).
Par ailleurs une des caractéristiques importantes des missions considérées est l'exigence de pouvoir être réalisées selon tous les niveaux d'engagement envisageables, des opérations temps de paix jusqu'à des niveaux de conflits généralisés. Ceci implique en particulier pour les opérations temps de paix ou temps de crise d'assurer une mise en œuvre sécurisée dans un environnement incluant entre autres la circulation aérienne (civile ou militaire) et le survol de zones habitées. Une grande attention doit être attachée à ces aspects, bien entendu en concertation avec les autorités concernées.

Le maintien dans la boucle de l'opérateur humain est justifié d'une part pour le contrôle de la charge utile (capteurs) et l'exploitation quasi temps réel des informations recueillies et d'autre part pour l'insertion du système dans son environnement opérationnel et tactique ; aucun de ces éléments ne justifie cependant que l'homme soit à bord de la plate-forme elle-même. Ceci en effet peut être obtenu par le biais de systèmes performants de communications et la mise en place de moyens externes de contrôle (« stations ») sans doute situés au sol et permettant :
- La mise en œuvre de la plate-forme,
- La mise en œuvre de la charge utile,
- Le lancement et la récupération du vecteur.

3.8. Seconde étape : les Avions d'Attaque Sans Pilote (A2SP)

3.8.1. Approche globale

Cette seconde étape est caractérisée par une exploitation plus poussée des degrés de liberté rendus disponibles par l'élimination de la présence de l'homme à bord, tant au niveau des concepts généraux que de la mise en œuvre des systèmes.

Les missions considérées sont celles des avions de combat, les missions candidates (actuellement) étant celles où les risques sont les plus importants pour les équipages. Parmi celles-ci se trouvent principalement :
- la mission de suppression des défenses sol-air,
- l'attaque d'objectifs de valeur (en général très défendus),
- la reconnaissance tactique et l'évaluation des dommages de combat.

Les missiles de croisière constituent une forme de réponse possible à l'élimination de la présence de l'homme à bord. Outre le fait que la plupart des missiles de croisière existants ne sont pas à ce jour contrôlables à distance-la philosophie « tire et oublie » (fire and forget) ne les rend pas aptes à réagir à des évolutions rapides de la situation et à l'attaque des objectifs d'opportunité- il convient également d'en considérer le facteur coût : :
- le coût unitaire des plates-formes de tir et du système associé,
- le coût des armements mis en œuvre (lié à leur portée et à leur précision),
- Le nombre de missions qu'une plate-forme peut réaliser en opération.

Combinés, ces éléments militent fortement en faveur de véhicules réutilisables capables de délivrer des armes potentiellement simples.

L'élimination des contraintes (recensées en introduction) imposées par la présence du pilote à bord permet d'envisager des concepts innovants de systèmes et véhicules ; par exemple :
- Concepts nouveaux de plates-formes (taille, formes, aménagements),
- Concept de stockage en temps de paix, associé à un entraînement des opérateurs basé sur la simulation,
- Optimisation du système pour la mission selon un nombre de critères accru (manœuvres, signatures),
- Un moindre recours à des technologies réputées chères (par exemple l'effet de la taille sur la signature qui peut permettre de se passer de l'emploi de revêtements absorbants),
- Cible d'emploi réduite induisant des marges réduites en conception (en particulier durée de vie limitée, domaine restreint).

avec pour conséquences probables (mais non démontrées !) des véhicules plus petits, plus légers et sans doute moins chers (à acquérir et à utiliser) que les chasseurs actuels et qui seraient en conséquence des solutions possibles au problème de fond des forces aériennes qui est celui du coût des systèmes d'armes.

La réflexion sur ces systèmes ne doit pas cependant se limiter aux plates-formes seules. En effet au travers d'une stricte substitution à un avion d'armes habité ou au travers de concepts novateurs tels que des capacités de perception distribuée, des attaques saturantes,... une approche globale au niveau système doit être réalisée. Celle ci devra couvrir :
- les autres éléments du dispositif et la logistique requise :
  - Dispositif Tactique, par exemple :
    - Contrôle-Commande (C2),
    - Autres avions de combat,
    - Ravitailleurs,
    - Avions de Guerre Electronique,
    - ...
  - Moyens de Soutien, par exemple :
    - Planification,

- Entraînement,
- Mise en œuvre,
- Maintenance,
- ...

- La composante humaine :
  - Rôle des opérateurs,
  - Qualification des opérateurs,
  - Quantification des opérateurs.

Pour ce qui a trait à la place des opérateurs humains dans la mise en œuvre de systèmes non habités, il est probable que la délégation totale à un opérateur non humain de décisions telles que le tir d'armes (associée à l'identification des objectifs et de leur environnement) ne sera pas envisagée dans un futur proche du fait de la complexité et du niveau de confiance que ces tâches requièrent de la part du système chargé de les réaliser. L'implication souhaitable de l'opérateur humain dans les opérations aériennes devra être obtenue au travers d'un poste de commande de théâtre qui pourra se trouver :

- au sol,
- dans un avion de type C3I,
- dans un avion d'armes (chasseur) intégré au dispositif d'attaque.

Bien que toutes ces configurations puissent être considérées, un point de vue partagé (mais dont le concept reste à démontrer) est que l'implication de l'opérateur et la confiance dans ses actions et décisions au cours des opérations, sera meilleure s'il se trouve à proximité du théâtre (mais néanmoins à distance ou en situation de sécurité). Cela permettra en outre, une simplification du système global et de l'Avion d'Attaque Sans Pilote (A2SP, la terminologie anglo saxone correspondante est Unhinabited Combat Air Vehicle UCAV) par le potentiel d'emploi des capteurs de l'avion et surtout par un système de communications plus simple (portée, latence, puissance rayonnée). Ces éléments plaident en faveur de concepts de dispositifs mixtes, ceux-ci préservant en outre des capacités d'emploi dans les autres configurations évoquées ci-dessus (opérateur déporté dans un avion.de commandement ou au sol).

3.8.2. Besoins techniques

Les problèmes évoqués ci-dessus se rapportent essentiellement à la définition globale du concept d'emploi des systèmes mettant en œuvre des Avions d'Attaque Sans Pilote et à leur insertion dans des dispositifs plus globaux. Ceci ne constitue cependant qu'une petite partie des problèmes complexes à résoudre. Des réflexions initiales menées sur ces concepts, en terme de contrôle, il peut néanmoins être dégagé, des thèmes techniques génériques à explorer, en tenant compte de la présence de l'opérateur dans certaines boucles de décisions/action et sachant que l'un des risques majeurs lié à la mise en œuvre de ces systèmes a trait aux limites de l'opérateur en terme de charge de travail ou de capacité à extraire les informations pertinentes :

- Précision, évaluation temps réel de la situation (dont identification des objectifs),
  - Elaboration de stratégies pour la prise d'information :
    - Prise en compte du contexte tactique (incertitudes, risques, enjeux),
    - Détermination des points d'observation du contexte,
    - Prise en compte des caractéristiques fonctionnelles des ressources de perception telles que :
      - performances (champs, résolution,...),
      - interactions avec la plate-forme (domaine spatial couvert, masques,...).
    - Prise en compte du domaine d'emploi des ressources de perception (ex signature, sensibilité à l'environnement météorologique, autonomie),
    - Nature des objets à observer (fixes, mobiles, signatures, taille,...).
  - Disponibilité préalable d'informations :
    - Planification préalable (préparation des missions),
    - Rafraîchissement des données (liens avec l'extérieur).
  - Corrélation d'informations perçues selon :
    - Des points d'observation différents (capteurs répartis sur plusieurs plates-formes),
  - Des modes de perception différents :
    - Nature des capteurs utilisés et de leurs sorties, par exemple Electromagnétiques, Electro-optique/infra-rouge,
    - Forme des informations fournies, par exemple : Informations synthétiques (pistes, plots), images,
    - Complétude des informations, pour assurer par exemple une localisation d'objectif (distance seule ou direction seule ou distance et direction).
    - Perception coopérative.
  - Extraction des informations utiles en terme :
    - De précision, en particulier lorsqu'il s'agit de localiser un objectif pour l'attaquer ensuite avec des armements de précision,
    - De nature en particulier pour les actions de Reconnaissance et d'Identification des objectifs.
  - Connaissance continue des capacités résiduelles du Système (Dispositif mixte) :
    - Etat des Ressources techniques (perception, traitements, actions) et des Consommables (carburants, leurres) et capacités d'utilisation (ex discrétion, météo),
    - Adéquation Ressources et Capacité :

        - Mission,
        - Survie,
        - Sécurité.
    - Reconfigurations techniques.
- Coordination des actions :
    - Planification globale,
        - Attribution des rôles,
        - Délégation d'autorité,
        - Résolution des conflits de ressources.
    - Planification individuelle à l'intérieur d'un domaine autorisé, niveau d'autonomie permanent ou ponctuel,
        - Déconfliction des actions programmées en terme de :
            - Trajectoire,
            - Emissions,
            - Tirs (armements, leurres).
- Réaction aux situations imprévues et planification :
    - Identification de la pression temporelle :
        - à l'échelle de la mission ou de la phase de mission en cours (de quelques secondes à quelques minutes),
        - au niveau de danger perçu pour l'homme (opérateur et autres) et pour les plates-formes en terme de sécurité (situation dangereuse et/ou défaillance du système) ou de survivabilité (face à des agressions externes).
    - Pertinence et temps d'élaboration des réponses.

et les conséquences techniques principales que ces contraintes amèneront sur le système :

- Puissances de traitement installées.
- Contrôle-commande fiabilisé secondé par la capacité du véhicule à assurer de manière autonome un certain nombre de tâches critiques en cas de perte des communications ou lorsque le contrôleur est focalisé sur d'autres priorités :
    - Chaînes de reconfiguration,
    - Prise en compte des tâches critiques pour la plate-forme et son environnement (par exemple : l'anti-collision sol et l'anti-abordage),
    - Conditions de fin de vol (recueil, destruction).
- Les communications fiabilisées et reconfigurables :
    - Niveaux de confiance dans les informations transmises (anti compromission, erreurs, reprises sur erreurs détectées),
    - Réactions pertinentes aux non disponibilités des liaisons de données (défaillances, intervisibilité, brouillage) et à leur caractéristique de prédictibilité et de réversibilité (routage des données).
- Les assistances à (aux) l'opérateur(s) pour les opérations multi-plateformes (un des problèmes qui se posent étant le nombre de plates-formes non habitées contrôlables simultanément par un opérateur) :
    - Capacité d'allocation dynamique des tâches aux acteurs tactiques en fonction de la situation et de l'activité de l'opérateur avec prise en compte de la pression temporelle ,
    - Assistance à la perception de la situation (structuration des données présentées, filtrages, formes de représentation, extraction des informations pertinentes),
    - Coopération entre les opérateurs humains :
        - Commonalités de représentation de la situation,
        - Compréhension mutuelle,
        - Assistances à la coopération.
    - Assistance aux tâches de contrôle et d'allocation réalisées par l'opérateur par mise à disposition d'outils de dialogue optimisés à cette fin.

Un élément complémentaire (mais fondamental si l'on se réfère au contexte géopolitique évoqué dans l'introduction) auquel devront satisfaire à des degrés variables les technologies ou techniques répondant aux besoins évoqués précédemment sera leur capacité à supporter des évolutions de cahier des charges des systèmes dans lesquels elles seront intégrés ; ces évolutions de cahier des charges pourront concerner :

- Le contexte d'emploi : nature des environnements tactiques amis et ennemis, nature des missions, règles d'engagement
- L'expertise d'emploi : connaissance technique des qualités et défauts des systèmes mis en œuvre, mise au point de règles tactiques d'utilisation

En effet, l'expertise d'emploi d'un système s'accroît avec sa durée d'utilisation, et les contextes d'emploi évoluent dans le temps ; l'expérience montre qu'il n'est pas rare que les ingénieurs découvrent que l'emploi que les opérationnels font des systèmes qu'ils ont conçus et développés diffère des hypothèses qu'ils avaient prises lors du développement initial (lesquelles avaient néanmoins été élaborées en accord avec les représentants de l'utilisateur final). Dans les classes de systèmes habités actuels la plus grande partie de cette tâche d'adaptation est prise en compte par les équipages ; ceci ne sera plus directement possible pour les avions de combat non habités.
Les techniques considérées devront donc permettre de créer les outils que les utilisateurs auront la capacité d'adapter à leur expertise opérationnelle et aux contextes nouveaux qu'ils rencontreront.
Cette exigence sera d'autant plus forte que la boucle de contrôle dans laquelle ces technologies seront utilisées

sera sensible au contexte effectif de mise en œuvre ; l'architecture des systèmes devra être conçue en conséquence de façon à minimiser les coûts et les délais d'adaptation (l'ordre de grandeur pouvant aller de quelques heures typiquement : planification des missions- à quelques mois typiquement : cycle d'élaboration et mise à jour des manuels d'emploi tactiques).

4. CONCLUSION

Ces quelques considérations qui ont permis de situer les concepts de systèmes non habités (de reconnaissance ou d'attaque) futurs vis à vis de leurs apports (technique, opérationnel, économique), n'ont pas vocation à être définitives, une des raisons principales étant que les concepts d'emploi opérationnels ne sont à ce jour pas figés. Malgré ces incertitudes, les réflexions déjà entreprises laissent prévoir que les technologies permettant de satisfaire les exigences fonctionnelles suivantes :

- La fusion et le traitement des données de capteurs provenant de plusieurs plates-formes,
- Les communications temps réel,
- La tolérance aux fautes,
- Les techniques de planification,
- Les assistances à l'opérateur humain pour :
    - Le contrôle simultané de plusieurs plates-formes,
    - L'interprétation de la situation (complexe, incertaine et fortement évolutive ; synthétique ou sous forme d'images),
    - L'aide à la décision,
    - La (re)planification de la mission,
    - La (re)configuration du système et des tâches allouées aux participants.
- Les interfaces homme-machines,

devront être développées et faire l'objet de démonstrations.

Dassault Aviation en tant qu'avionneur, architecte industriel et intégrateur de systèmes complexes réunit, avec ses partenaires industriels et les organismes de recherche (tant en France qu'à l'étranger), les compétences requises pour concevoir et développer ces types de systèmes. D'ores et déjà des travaux menés par la société (seule ou avec des partenaires tels que l'ONERA) dans le cadre de programmes conduits par la DGA, ont permis d'approfondir les réflexions sur les sujets évoqués. Leur poursuite planifiée au travers d'études de concepts, d'actions de recherche et de démonstrations préliminaires au sol, va permettre d'orienter les démonstrations à réaliser et d'identifier les technologies à développer en priorité pour acquérir la faisabilité de concepts d'avions d'attaque sans pilotes et qui, dans le futur, pourraient s'insérer dans des dispositifs opérationnels composites en complément des systèmes avec pilotes.

UAV Requirements and Design Consideration

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1. SUMMARY

This paper deals with the UAV requirements based on the battlefield experiences. UAV roles in tactical areas and constraints, which affect the UAV mission to be conducted, are explained and suggestions are given. Constraints; such as environmental conditions, effects on UAV missions, battlefield situations, operational restrictions and technological limits are overviewed.

Based on the current applications and systems, some remarks are presented. Considering the future requirements; air vehicle performance, data link and expected payload specifications for a general UAV system are addressed. Assessments and recommendations are given for system design consideration.

2. INTRODUCTION

There have been increasing demands in modern world to use UAV systems as Intelligence, Reconnaissance, Surveillance and Target Acquisition Systems. Although requirements for UAVs change based on the missions to be carried, expectations are generally similar for each type. Cost-effectiveness, reliability, maintainability, usefulness and operational availability are some of the requirements that all systems should have. Besides these, all UAV system should also fulfill certain basic requirements, as outlined below:

- Performing efficient surveillance and reconnaissance missions for the armed forces
- Day and night operations
- Operating in a wide range of weather conditions
- Various altitude operation
- Beyond Line-of-Sight (BLOS) operation
- Real-time operation
- Multi-mission capability, etc.

These requirements help to define the UAV system specifications in terms of the performance parameters of the following basic subsystems:

- Air vehicle
- Ground control station
- Payloads
- Data link
- Support equipment

Performance parameters are closely interrelated and usually shape these subsystems. At the beginning of the program definition phase, requirements are always beyond the technological advances. However, an optimum cost-performance system definition can be reached by adequate trade-off studies, taking operational concepts and technological capabilities as parameters.

Requirements and system specifications for each subsystem are considered in the next section of this paper. Following these assessments, general issues such as reliability, availability, maintainability, mobility, transportability, deployability, sustainability, environmental conditions, survivability, safety, interchangeability and modularity aspects of UAV systems are examined.

3. SUBSYSTEMS

3.1 Air Vehicle

Radius of action is defined as the maximum distance that the UAV can travel away from its base along a given course with normal mission payload, carry out its intended mission, and return without refueling, allowing for all safety and operating factors This distance is directly dependent on the level of military unit that will operate the system and will ideally cover their area of interest.

The endurance at the radius of action is an important parameter that defines the coverage of the air vehicle at the specified loiter speed, typical operating altitude and sensor properties. Endurance is mainly dependent on the air vehicle aerodynamic design, and fuel amount carried. Fuel increase capacity is usually a problem since the space and weight available for fuel is limited. The aerodynamic designs for high endurance systems usually result in powered-glider type configurations.

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

Total endurance, as the name implies, includes the total time from take-off to landing. This parameter is defined based on the mission duration that user wants to use air vehicle on the sky without landing. A high endurance system usually does not have a high cruise or dash speed and may spend a considerable time during the climb, cruise-out, cruise-back and descent phases, especially when the radius of action is far.

Typical operating altitude can be defined as the altitude where the specified payload performance (e.g. image quality) and coverage can be obtained with the desired mode of operation (through data link or autonomous recording). Higher altitudes are desirable for better coverage, survivability and line-of-sight for data link operations. However, there are several limitations for achieving a high operating altitude. Apart from the payload technical limitations, the higher altitudes may necessitate the use of specially treated piston engines, or even turbine engines. Turbine engines have higher power-to-weight ratios and lower specific fuel consumption, but the costs associated are usually 3-4 times of a comparable piston engine.

Operational altitude also depends on the air traffic control limitations. It should not be forgotten that unmanned air vehicles are dangerous objects for manned air vehicles in the sky. Therefore this parameter should be considered in terms of air traffic control.

Maximum altitude is important especially if operations over mountainous terrain are involved. The same limitations for the operating altitude also apply for the maximum altitude. One important consideration for the maximum altitude is that it is a service altitude, meaning a 100-feet/min-climb rate, and not the absolute altitude, which takes a long time to achieve.

The **cruise and maximum speed** is dependent on the engine power and aerodynamic design of the air vehicle. As mentioned before, a high endurance requirement is conflicting with a high speed requirement since high endurance designs usually have efficient small engines (compared to their size) and big wings with high drag. Cruise speed requirements are driven by the timeliness of mission.

Loiter speed is usually the optimum speed for endurance and is somehow slow (close to the stall speed). The loiter speed directly affects the payload coverage area.

Climb rate is related with the speed and altitude performance of the air vehicle. It is an operationally important parameter especially when the terrain to clear is close and/or steep. A high climb rate also improves the survivability of the air vehicle.

3.2 Ground Control Station

The Ground Control Station (GCS) is the operational control center of the entire UAV system (Figure 2). It controls the launch, flight and recovery of the air vehicle, receives and processes data from the payloads, controls the operation of those payloads (often in real time), and provides the interface between the UAV system and the outside world (6,7).

Some of the expected functions of a GCS can be described as follows:

3.2.1 General

GCS should

- provide an open system architecture so that can support the future requirements; as the system expands in the future, the system architecture should support it without restructuring the GCS completely.
- be scalable so that it can be used in different platforms (ground, airborne, ship).
- be modular so that the system attributes can be changed by physically changing modules.
- be flexible so that as the user and mission requirements vary, the system attributes can be easily changed.
- be capable of executing maintenance software and displaying appropriate status results.
- have ergonomically designed operator controls and displays.
- be capable of operation within the specified environmental conditions.
- be easily deployed and transported.

3.2.2 Mission Planning, Control and Monitoring

GCS should

- have the functionality to allow the operator to generate and process UAV mission plans.
- permit dynamic mission and payload retasking during all phases of operational mission execution.
- provide the system functionality necessary to upload a flight route plan and payload plan to the UAV via the selected system data link as well as direct ground connection.
- automatically check the validity of the intended mission plan prior to being uploaded including altitude constraints, payload constraints, data link range constraints, airspace restrictions, fuel

limitations, threat constraints, data link terrain masking effects, and Loss of Link Plan.

- have the capability to control and monitor AV, payload, data link, and C2 interfaces during the execution of a mission.
- have the capability to control and monitor multiple UAVs.
- pass control of a UAV to another GCS, and take control of a UAV from another GCS.
- implement an emergency action plan to control the AV during equipment failures.
- monitor payload and telemetry data in real-time, and record all the data for future review and processing.
- receive, process, display and exploit the payload output data.
- display data on the same monitor from more than one payload simultaneously.

3.2.3 C3 System Interfaces

GCS should

- provide interfaces with various C3 systems to satisfy the operational requirements.
- manage all aspects of C3 system interfaces to include receiving, processing, and transmitting tactical information.

3.2.4 Safety and Security

GCS should

- have appropriate cautions and warnings if the UAV system enters into an unsafe operating mode.
- provide the required information to allow the operator to maintain safe separation from other aircrafts (manned or unmanned).
- be capable of restoring power in sufficient time to avoid loss of UAV control during power outages.
- be designed to protect its communication and data links against enemy Electronic Warfare (EW) threats and physical destruction.

3.3 Payloads

The term "payload" is referred to the equipment that is added to the UAV for the purpose of performing some operational mission (Figure 2). In other words, the equipment for which the basic UAV provides a platform and transportation. This excludes the flight avionics, data-link and fuel.

Using this definition, the payload capacity of a UAV is a measure of the size, weight and power available to perform functions over and above the basic ability to take-off, fly around and landing.

The types of payloads carried by the air vehicle are defined by the different mission requirements of the user. Reconnaissance payloads are the most common used by UAV systems and are of the highest priority for most users. The primary payload technologies for reconnaissance mission are Electro-Optic (EO), Infrared and Synthetic Aperture Radar (SAR). The key issues associated with them are: having the resolution to see far enough and at the same time over a wide enough area, and having a payload that is small, light, low power consumption and at an affordable price, such that a UAV can carry it for a period long enough to satisfy the end users' needs. Additionally, in conjunction with other sensors, such as range finders, and the UAV's navigation system, the payload may be required to determine the location of the target with a degree of precision that depends on the use to which the information will be put (6,7,8).

For the users and designers of UAV systems, choosing the optimum payload for the mission requirements is of prime importance. The relative advantages of the sensor types and their potential for satisfying a range of common mission goals should be evaluated. Technology is advancing rapidly in many sensor and signal processing fields and the probability (potential) for new solutions to current problems should be considered.

Some mission require to put and control more than one payload at same time. But AV size, data link and interface limitations and GCS control capabilities allow to have this request.

Whatever the operational requirements are for payloads, the other important point is to have payload modularity. In another words, different types of payloads such as reconnaissance, Electronic Warfare (EW), mine detection, NBC, meteorology and etc. should be easily plugged in the AV without SW and HW modifications.

Having payload data in GCS is not sufficient itself. Evaluated data should also be disseminated to the active units in real time through the well-established C^4I network.

3.4 Data-Link

The data-link is a key subsystem for any UAV system. It provides two-way communication, either upon demand or a continuous basis. An up-link provides control of the air vehicle flight path and commands to its payloads. The downlink provides both a low data rate channel to acknowledge commands and transmit status information about the air vehicle and a high data rate channel for payload data such as video and radar.

The data-link typically consists of two major subsystems; the Air Data Terminal (ADT, the portion of the data-link that is located on the AV) and the Ground Data Terminal (GDT, the equipment on the ground, (Figure 2)). Payload data can also be received through the use of passive remote video terminal (Figure 3).

On a battlefield the UAV system may face a variety of EW threats, including direction finding used to target artillery on the ground station, anti-radiation munitions (ARMs) that home on the emissions from the GDT, interception and exploitation, deception and jamming of the data-link. It is highly desirable that the data-link provides as much protection against these threats as reasonably can be afforded.

Depending on the mission and secenarios, the desirable attributes for a UAV data-link can be summarized as follows (6,7):

i. Worldwide Availability of Frequency Allocation: Operate on frequencies at all locations of interest to the user in peacetime as well as being available during wartime.

ii. Resistance to Unintentional Interference: Operate successfully despite the intermittent presence of in-band signals from other RF systems.

iii. Low Probability of Intercept (LPI): This is highly desirable for the up-link, since the GCS is likely to have to remain stationary for long periods of time while it has air vehicle(s) in the air, making it a target for artillery or homing missiles if it is located.

LPI can be provided by frequency spreading, frequency agility, power management, low duty cycles and using directional antennas.

iv. Security: Unintelligible if intercepted, due to signal encoding.

As a general rule, it appears that security is of only marginal value in a UAV data-link. However, some intelligence missions could introduce security requirements.

v. Resistance to Jamming: Operate successfully despite deliberate attempts to jam the up and/or downlink.

The overall priority of anti-jam capability depends on the threat that the UAV is expected to face and the degree to which the mission can tolerate jamming.

vi. Resistance to Deception: Reject attempts by an enemy to send commands to the air vehicle or deceptive information to the GDT.

Deception of the up-link would allow an enemy to take control of the air vehicle and either crash, redirect, or recover it. Deception of the up-link only requires getting the air vehicle to accept one catastrophic command (e.g., stop engine, switch datalink frequency, change altitude to lower than terrain, etc.). Deception on the downlink is more difficult, since the operators are likely to recognize it. Resistance to deception can be provided by authentication codes and by some of the techniques that provide resistance to jamming, such as spread-spectrum transmission using secure codes.

Line-of-Sight range constrains, AV/GCS relative position, link availability, data characteristics, EW environments and installation requirements are the main characteristics to define data link for a UAV system (6). Data link can be established by hub/prime site deployments and utilization of relays (ground, airborne, satellite) (Figure 3). Operational cost, missions, deployment area and above characteristics are important parameters to choose the means that extend the mission radius. Since users never prefer link loss between air vehicle and ground control station during real time operations, both telemetry data and video link should be well established.

Since the interaction between the data-link and the rest of the UAV system is complex and multifaceted, the design tradeoff between them should occur early in the overall system design process. This allows a partitioning of the burden between the data-link, processing in the air and on the ground, mission requirements, and operator training.

4. GENERAL UAV SYSTEM REQUIREMENTS AND RECOMENDATIONS

4.1 Reliability, Maintainability, Availability

System reliability is a very important parameter and is a direct result of system hardware and software maturity. Hardware failures and software bugs are common during the development stage of the system and directly effect system reliability. Among the UAV systems, engine and software are seen to be the most critical items. Reliability is especially critical for the bigger and more expensive UAV systems that can carry multiple payloads for extended duration.

Mission reliability is defined as the probability that the UAV system will perform failure-free during all phases of its specified mission, including pre-flight, take-off, cruise-out, payload operation, data link operation, cruise-back and landing (3). Most accidents do occur during the landing phase, and automatic methods of landing are becoming more and more common to reduce human error and weather-related problems. Icing is another common problem that affects the mission reliability.

Another important reliability parameter is the **Mean Time Between Loss** (MTBL) figure, which can be improved by the redundancies in the system. MTBL directly affects the Life Cycle Cost of the UAV system.

<u>Maintainability</u> is the ability of the system to be retained in or restored to operating condition when maintenance is performed by personnel having specified skills using prescribed procedures and resources at each prescribed level of maintenance and repair. Mean Time To Repair (MTTR) or direct maintenance man-hours per flight hour (DMMH/FH) are frequently used parameters to measure the maintainability of a system. Number of LRUs, accessibility features, Built-in-Test (BIT) and other automatic testing utilities improve maintainability.

<u>Operational availability</u> is the probability that a system is operable and ready to perform its intended mission at any given time in the specified operational environment. It is predicated on the design factors of reliability and maintainability, and considers maintenance (preventive and corrective), supply (logistics) and administrative downtimes.

4.2 Mobility, Transportability, Deployability

Mobility, transportability and deployability of UAV systems are largely determined by the existing operational requirements and available infrastructure.

<u>Mobility</u> is the capability of the system to be moved from place to place while retaining the ability to fulfill the primary mission (4).

<u>Transportability</u> is the capability of the system to be moved by towing, self-propulsion, or carrier (highway, railways, waterways, and airways).

<u>Deployability</u> requirements are defined in terms of numerical limits (for example two C-130 aircraft). The limits should be related to the transport of a specific number of items over a specific distance for a specified period of deployment (which defines spares and supplies required) (5).

A tactical UAV system usually requires more mobility and transportability than a large UAV system that will operate from the same base for extended periods of time. The mobility requirements for tactical systems necessitate take-off and landing operations without the need for a prepared runway. The design solutions may involve Short Take-off and Landing (STOL) operations from unprepared runways, catapult launching or VTOL air vehicles.

4.3 Sustainability

<u>Operational Sustainability</u> is the ability to maintain the necessary level and duration of operational activity to achieve military objectives. It is a function of providing for and maintaining those levels of ready forces, material, and consumables necessary to support military effort (4). The UAV system should be capable of completing a sustained operation of specified duration in the operational site without resupply or support from personnel other than system crew, in order to have high availability rates. This is especially important for the highly mobile tactical UAV systems.

4.5 Environmental Conditions and Electromagnetic Effects

UAV system design should allow operation, storage and transportation in user specified operational environments. The environmental conditions typically include temperature, humidity, precipitation, wind speed (steady and gust), dust, solar radiation and icing. Separate specifications are usually required for each system mode; such as operation, storage and transportation.

The UAV operational experiences indicate that high altitude/low temperature, icing and wind (especially during landing and at high altitude) conditions form the most limiting environmental cases. Measures should be taken for icing problem, but its impact on cost and performance should not be overlooked.

The electromagnetic effects are very important for UAV systems that depend heavily on the avionics and data link for carrying out its mission. This is especially critical in communications relay and SIGINT operations (2) and shipboard applications.

4.5 Survivability and Vulnerability

It is essential that the UAV's level of detectability permits continued operations in a hostile area (3). Usually the following measures are required:

- Small visual silhouette
- Small infra-red signature
- Small radar cross section
- Small electronic emission
- Small acoustic emission

4.6 Safety

The safety measures should be taken so that undesired consequences are kept to a minimum during a hazardous event. Risk of personnel injuries or material damage due to hardware, software, procedural or environmental hazards must be at acceptable levels. Air vehicle emergency modes and flight termination systems improve the operational safety. However, larger UAVs might have space and weight limitations for termination system, and therefore must have better reliability figures. Using communications relay between GCS and Air Traffic Control (ATC) is a good solution to improve the air traffic safety.

4.7 Interchangeability and Modularity

Interchangeability simply means that all parts having the same manufacturer's part number are directly interchangeable with each other, without any alteration.

The optimal concept for users of UAV systems would be a modular generic type of payload with pre-integrated specialized instrumentation available for all UAVs. Air vehicle integration will then consist of merely plugging in the payload and connecting power and data cables (6). Interchangeable/modular payloads allow much shorter Mission Change Times (MCT) which is very critical.

4.8 Growth Potential

The UAV system must facilitate upgrading to accommodate various sensor payloads. The growth potential should also be considered in the following areas:

- Extended payload range
- Air vehicle capability for spare weight, volume and power consumption
- Air vehicle capability for spare interfaces with avionics system
- Data-link bandwidth capabilities
- Ground system capability for operating future payloads
- Computer resource reserved capabilities for memory, timing, etc.

5. CONCLUSION

In recent years, the high demand for UAVs has resulted in quest for technological advancements expected from these systems. Air vehicle, data link, payload, ground control station and other sub-systems require different technologic areas of expertise on their own. System design therefore became an important factor since all these sub-systems, which effect the operational mission directly, require different disciplines of expertise.

In these paper recommendations on design criteria, which will enable the future requirements of generic UAV, systems for reconnaissance and observation purposes have been given.

6. ACKNOWLEDGEMENT

The author would like the acknowledge the help and support of Serhat Erdemir, Remzi Barlas and Mehmet Zaim.

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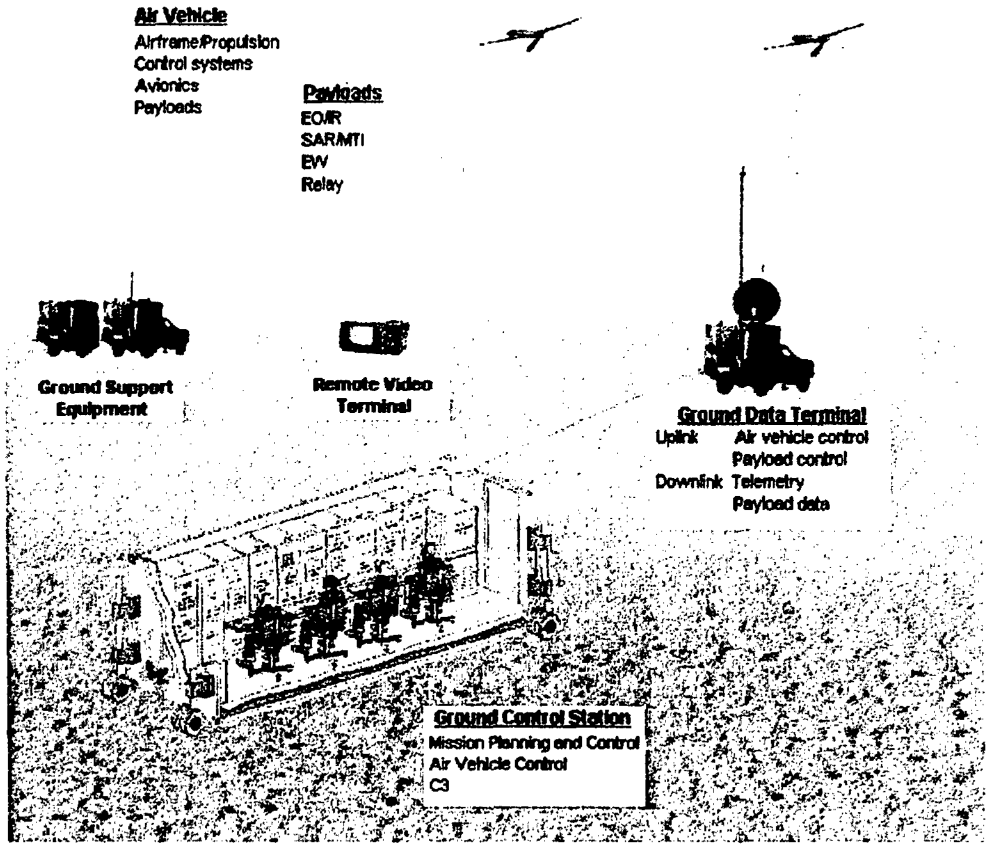

Figure 1. Unmanned Aerial Vehicle System

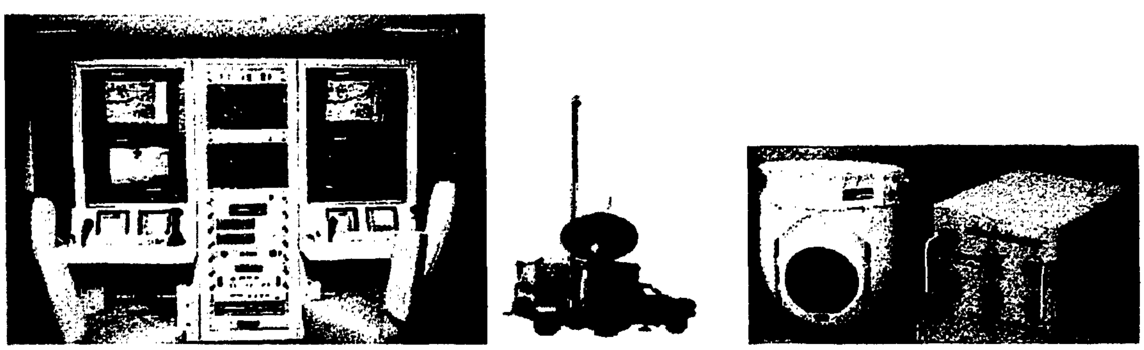

Figure 2. GCS/GDT and Payloads

Figure 3. Remote Video Terminal

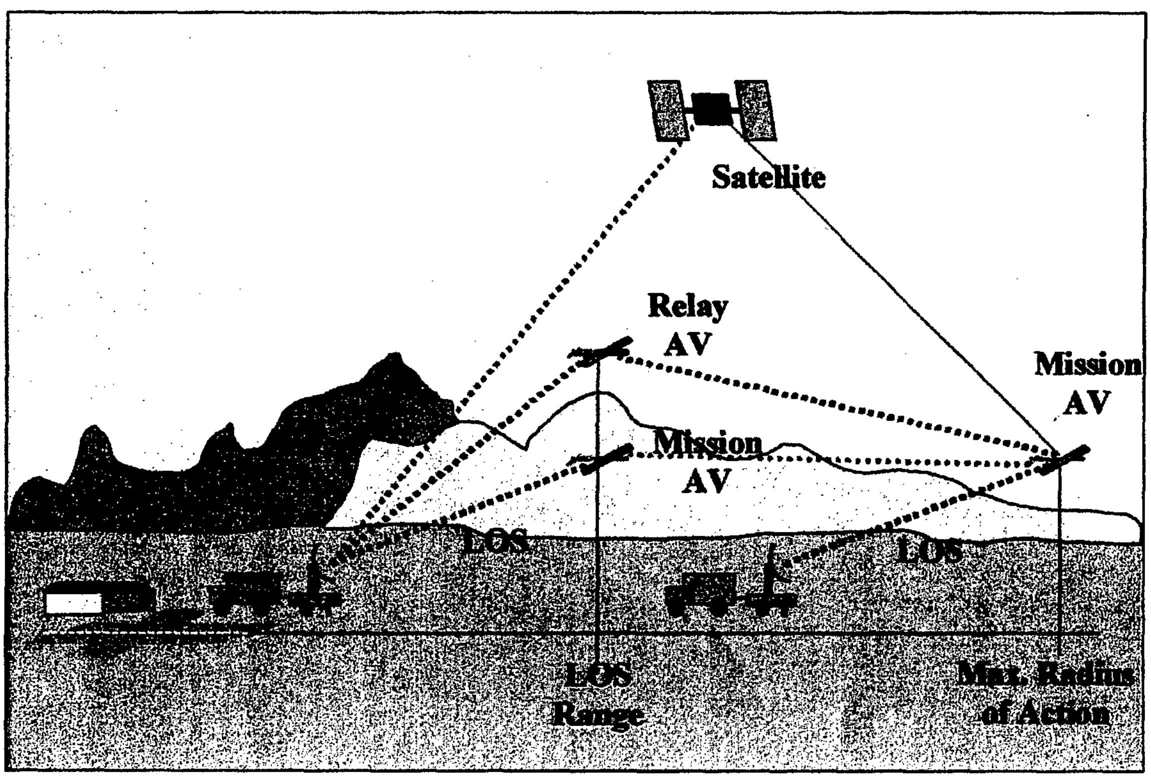

Figure 4. Concept of Operation

An analysis on Operability of Tactical Unmanned Aerial Vehicle Systems over Turkish Territory

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The requirements for operational arena of Tactical Unmanned Aerial Vehicles (TUAV) are highly effected with the geographical and weather conditions. A TUAV requirement for a flat terrain with moderate weather over the year varies dramatically from a mountainous terrain with severe weather conditions. Availability of the infrastructure such as airfields, highways is another contributing factor towards the system requirements. Transportability brings another concern when TUAV system is to be deployed by existing aerial assets. This paper evaluates the conditions of Turkish territory and infrastructure; transportability/mobility and therefore tries to approach to the best set of requirements for a TUAV system, with a review of crew and ground vehicles that can operate in Turkish Armed Forces.

WHY TACTICAL UAV SYSTEM:

To bring real-time information to the front-line commander is the major driving force to utilize a TUAV system. The areas of interest in several cases may begin from 50 km. in range and sometimes extend up to 200 km. Even though a long range/Endurance UAV (EUAV) may well serve for strategic operations, to provide tactical picture to several front-line units can sometimes be ineffective if not impossible with those systems. To be able to re-deploy a UAV system according to the changing threats/conditions is critical and requires a local/mobile control station for a EUAV. A TUAV system, on the other hand can be deployed as a whole.

The two most challenging performance parameters for UAV systems are time-on-station (TOS) and time-on-transition (TOT). TOT can be defined as total time spent to fly to/from the mission area, whereas TOS, as the name implies, is the time over the target area. These parameters combined with coverage area forms the critical threshold between TUAV and EUAV's. Today's fast moving land/sea based threats requires a rapidly responding reconnaissance units. TOT for regiment or brigade level deployed UAV's should have a maximum value of one hour. This calls for either a fast-flying UAV that can fly to station from long-distance airfields or a rather slower UAV system to be airborned within 50 kms of range.

GEOGRAPHY OF TURKEY

Turkey, with 780,000 sqkm of land has a variety of geographical and meteorological areas. An analysis of a UAV system with various ranges of operation shows the comparison of 50km, 100km and 150km circles. Figure 1, Figure 2 and Figure 3, illustrate the distribution of these ranges of operation circles over Turkey with maximum possible coverage area.

The Table 1 shows the number of circles to cover Turkey, and percentage of these which has airfield within their coverage area. The situation will further be limited if major areas such as South-Eastern sector of Turkey is considered. (Zone SE)

Table 1 Airfield Coverage

	# of circles	airfield %	airfield % Zone SE
50 km	129	47	43
100 km	46	90	80
150 km	25	96	83

A UAV system to fly at 55 kts.(100 km/hr) with 10 hrs of endurance will have a flight profile like in Figure 4. Based on this timing, Figure 5 illustrates the number of sorties required to obtain a +24 hrs of coverage of a mission area.

As seen on these figures, TOT is a very critical factor on system effectiveness. Shortening this parameter certainly improves the operability of the system and decreases the number of sorties required.

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

Increasing the speed of the vehicle can help time savings on TOT, however to fly faster, engine power should be increased which results in higher fuel consumptions. Therefore the most effective solution to keep TOT at minimum for TUAV system appears to be stationing closer to the mission area. This will also have additional benefits like :

1. Quick reaction time to be on station with sudden threats.
2. Spend minimum time to recover in adverse conditions like severe weather changes (icing) or system malfunctioning.

Table 1 shows that increasing range of operation to 100 km. favors towards conventional UAV's (wheeled type, airfield requiring) with respect to catapult launched/chute recovered systems. Even in Zone SE, the situation appears acceptable.

However, the line-of-sight (LOS) data-link will bring some drawbacks while flying over this mountaneous territory. The aircraft either have to fly high to talk to Ground Control Station (GCS) which results in lower resolution of payload images or utilize ground/airborne data relay systems to talk to even ranges like 100 km. This being an additional complexing element to TUAV system would exceed the scope of being small and versatile.

For TUAV systems with 50kms of range since the airfields will not be available at ranges of interest, new solutions need to be created:

1. The aircrafts should be operable from semi-prepared runways. This can be a solution for some areas, though it can not be applied to all coverage areas especially for Zone SE.
2. Take-off/landings (TOL) should not require runways. This being a better solution with 100% coverage even at a mountaneous area, will bring additional requirements and options to TUAV system :

Vertical TOL UAV systems: To take-off from a designated area is not complicated for these vehicles. In addition to that where landing accuracy needs to be within 1 meter or so, VTOL UAV's appear to be the best solution. Therefore, especially for over the ship deck operations, VTOL UAV system is the best and only solution.

The major drawback of VTOL systems is the limited payload capacity compared to the similar weight/ powered fixed wing-conventional UAV systems. This is due to the nature of vertical flight where a bigger engine is required for a safe take-off/landing which has great implications on fuel-weight and range or endurance.

Catapult Launch/Chute Recovery systems: To perform an assisted take-off by means of a catapult, launcher or rocket, is again acomplicated solution to certain extent. This solution being less payload capable compared to wheeled aircrafts, is better than VTOL UAV's in terms of capacity or performance. If landing accuracy has a margin about 100 m.'s, this solution is the best of non-airfield requiring options.

Based on these evaluations especially for Zone SE tactical operations where a landing accuracy can be tolerated to 100m.'s, a catapult launched/chute recovered TUAV system can possibly provide the best effectivity.

TRANSPORTABILITY/MOBILITY

Fast-moving threats have great influence on the requirements of TUAV's. Unlike EUAV's, tactical commanders have the necessity to deploy TUAV system elements to varying distances very frequently.

For short range deployments, TUAV system has to be packed, moved and prepared back for flight in comparable times to its flight time. Like TOT parameter, TUAV system with all ground elements should be in move in less than an hour after the recovery. Even though there won't be any aircraft flying during the move, to save time some basic functions such as mission planning, backbone communication, flight de-briefing should be operable if needed. Similarly at the new launch area, total time to fly from parking should again be less than an hour.

The highways and operational areas especially on Zone SE, requires ruggedized moving vehicles with some off-road capability. Therefore unlike EUAV systems where system generally stays on an airfield, TUAV vehicles and trailers should be self-sufficient, self-sustaining rather small scale systems.

Instead of shelters temporarily loaded on trucks, ground shelters and other equipment should be an integral part of the moving vehicles. See Figure 6 and Figure 7.

In the case of +24 hrs. coverage requirement, which can be obtained with three aircrafts, Ground Support Vehicle (GSV) carrying capacity should not exceed four unmounted vehicles/payloads. Total number of ground vehicles should be two or max. three each with support trailers like Ground Data Terminal (GDT) or power generators.

For long distance deployments all vehicles and trailers should be sized to fit in cargo aircraft of TuAF. It is expected to limit number of sorties to minimum but even light transport aircraft CN-235 should be able to lift some basic elements. An analysis of cargo compartments of these aircrafts show that the system outer dimensions should fit in the envelope as shown in Table 2.

Table 2 Internal Dimensions of Cargo Aircrafts

	C-130	C-160	CN-235
X	1250 cm	1350 cm	965 cm
Y	302 cm	315 cm	236 cm
Z	271 cm	200 cm	190 cm

where X,Y and Z dimensions are length, width and height of cargo compartments respectively.

CREW REQUIREMENTS

In case where a TUAV system consisting of three/four aircraft, GCS, GDT and support equipment can be packed into two integrated ground vehicles and their trailers, the number of personnel to move and operate this sytem becomes a very important parameter. This, being a very important factor to determine number of consoles and task distribution, requires a compact, multi-roled team to accomplish the mission.

It is expected to perform missions including two simultaneously flying aircraft by only six well-trained personnel.

Unit Commander (UC) : Being essentially a reconnaissance team, unit commander is responsible from the complete flight operation of TUAV system. Pre-flight mission planning, backbone communication, payload operations and image/data evaluation tasks are expected to be performed by UC.

First Pilot (P1) : Being senior pilot of the unit and second commander, this serviceman is responsible from preparing and flying #1 aircraft and assisting flight planning.

Second Pilot (P2) : Being second pilot, this serviceman is responsible from preparing and flying #2 aircraft, recovering and performing O-level maintenance on aircrafts. He/she can also operate payload system.

First Payload Operator (PL1) : All payload operations on GCS especially for #1 aircraft and O-level maintenance of payloads, fall within the responsibilities of this serviceman.

First Technician (T1) : This serviceman is responsible from preparing ground systems to flight after deployment, O-level maintenance of ground vehicles, GDT and generator. During deployment, driving task of one ground vehicle belongs to this serviceman.

Second Technician (T2) . Similar to T1, this serviceman performs tasks on ground systems and drives second ground vehicle.

VEHICLE REQUIREMENTS

In order to fulfil the requirements of missions, transportation, mobility in Turkish territory, TUAV system vehicles should be arranged with the following configuration. This will also let system to comply with minimum crew requirements.

Ground Vehicle No.1: (GCS) This vehicle to carry integrated and sheltered ground control station is the heart of the system. Inside the shelter, there exist two consoles with an extension for a third laptop workstation and accommodation for three crew. One workstation with high-resolution graphical display is allocated for payload operations and can display real-time video or imagery. Besides payload tasks during the mission, it can also be utilized for post flight analysis by means of playing recorded payload imagery to perform intelligence tasks regarding targets involved. Second task is especially critical for payload data evaluation and also enables the operator to plan consequent flights. This utility should be operable even when TUAV system is in movement towards new deployment area.

The other workstation is used for flight planning and execution, and operated by mission planner/pilot. With the graphical representation of digital maps and airborne status, the pilot can re-plan flight path or manually fly the vehicle. For emergency reasons the tasks of these two workstations should have switching capability.

All system data including payload imagery should be recorded; and a hardcopy format output such as videotape or printed material should be available.

Second important task of GCS vehicle is communications. The radiating segment of the system, GDT, is planned to be mounted on a trailer and towed by this vehicle. Even on the move, some communication capabilities should be available to TUAV staff to basically include backbone communication to the headquarters and front-line commanders. Once the system is deployed and becomes operational at the mission area, the GCS-GDT couple works to communicate with air vehicle(s). At this place, GDT should be detached from the vehicle and displaced to a safe distance to GCS to avoid airborne attack damages.

A closed system communication (intercom) should be established between GCS and ground personnel. This utility, together with an external aircraft controller system will enable ground personnel to prepare or test other vehicles on ground without any RF radiation. The same controller system with LOS link capability, provides a backup aircraft control to recover already airborned vehicle if there exist a GCS system failure.

Ground Vehicle No.2 (GSV) This vehicle to carry three/four dismounted aircrafts is the support segment of TUAV system. While deploying, this vehicle can house both aircrafts and payloads at sheltered, safe closets. The launching equipment should be mounted to this vehicle while taking transportability requirements mentioned above into consideration. A tent to perform outdoor operations such as complete aircraft testing should be available with this vehicle. An intercom capability to talk GCS is another requirement. Figure 8 illustrates a complete TUAV system with all ground elements.

The main electrical supply of the whole system is a generator. Due to spatial requirements, this should be mounted on a trailer to be towed by GSV. Another important requirement associated with the generator and all running engines is to be able run with same type of fuel. This being a very important factor in terms of practicality of the system, will certainly avoid different fuel storing requirements. MOGAS or heavy-fuel for diesel engines will let system be operable with readily available fuel sources. This selection should involve everything including aircraft engines, ground vehicle engines and generators. The sufficient fuel for a complete mission should also be stored either in generator tank or GSV tank.

CONCLUSION

TUAV system requirements for Turkey have some peculiarities related with the operational conditions. Based on existing infrastructure of airfields, highways; a TUAV system with 50km. of radius of operation has to be of launched/chute recovery type. The whole system, to be a quick response unit for changing threats; should fit into existing cargo aircrafts and should have two well integrated ground vehicles with towed trailers. Common fuel concept should be applied to all system elements, and most important of all, to increase effectiveness, the complete system should be operable minimum number of personnel not to exceed six for a two ground vehicle version.

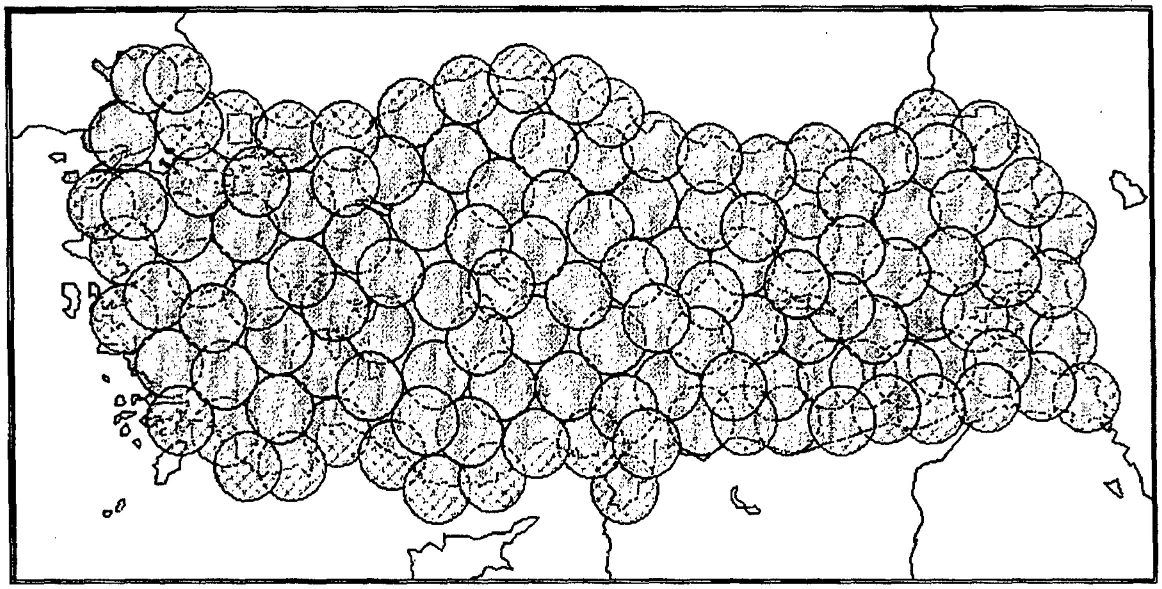

Figure 1 50km Range Coverage

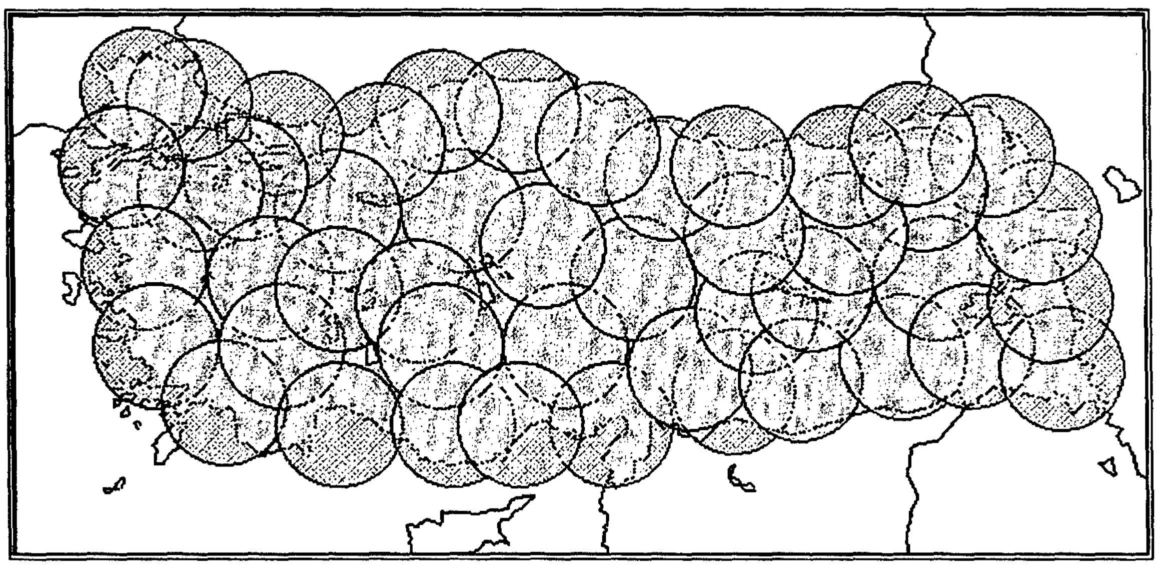

Figure 2 100km Range Coverage

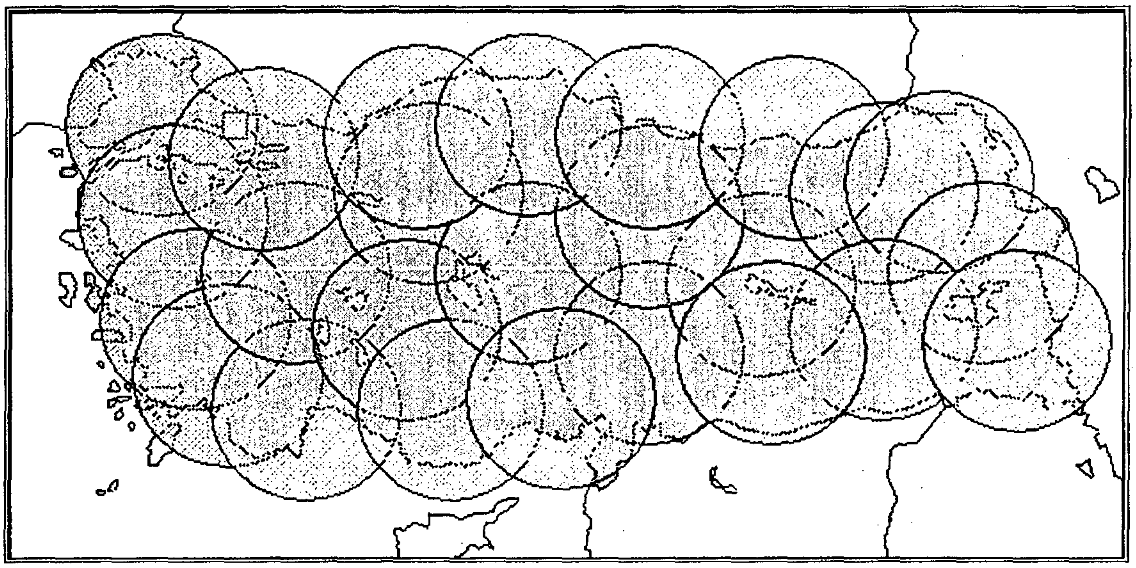

Figure 3 150km Range Coverage

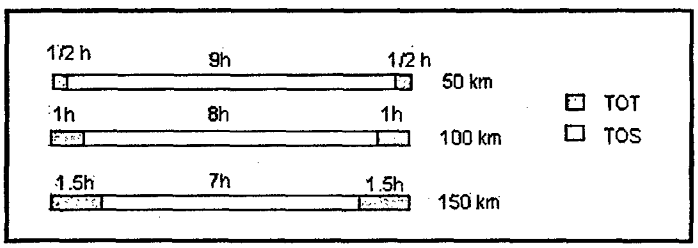

Figure 4 Flight Phases vs Ranges

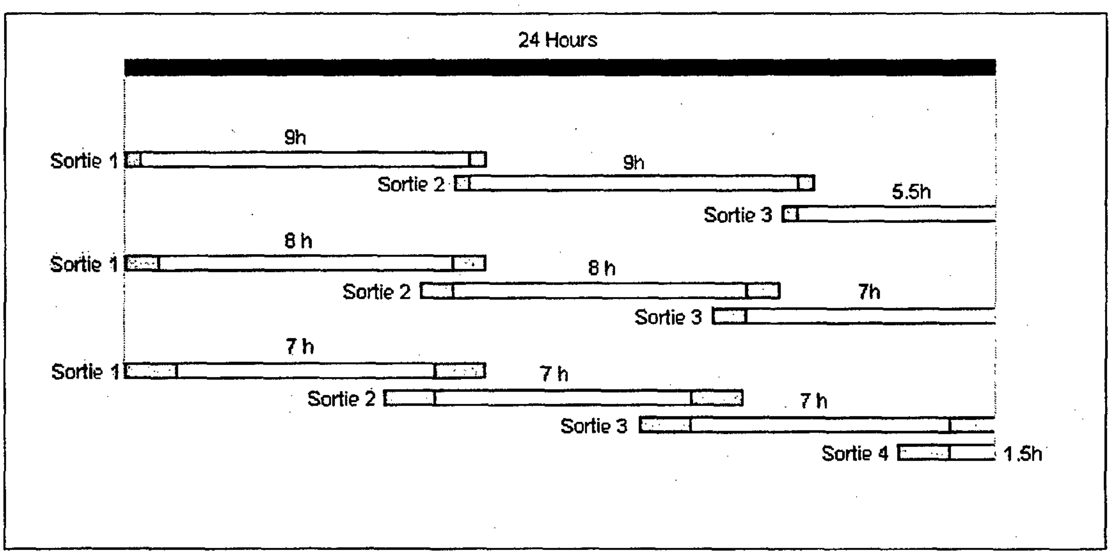

Figure 5 Sortie Requirement for +24 hrs of Coverage

Figure 6 GCS Shelter loaded on Truck

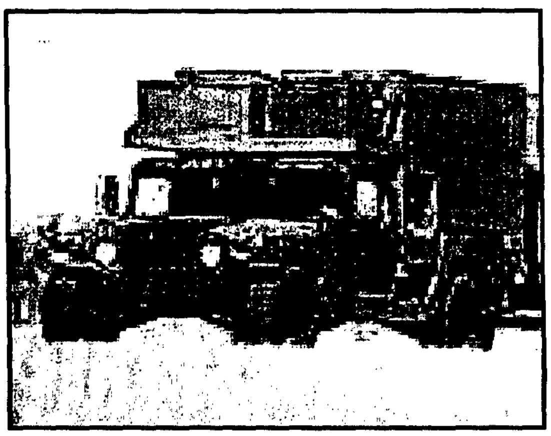

Figure 7 GCS Shelter integrated on Truck

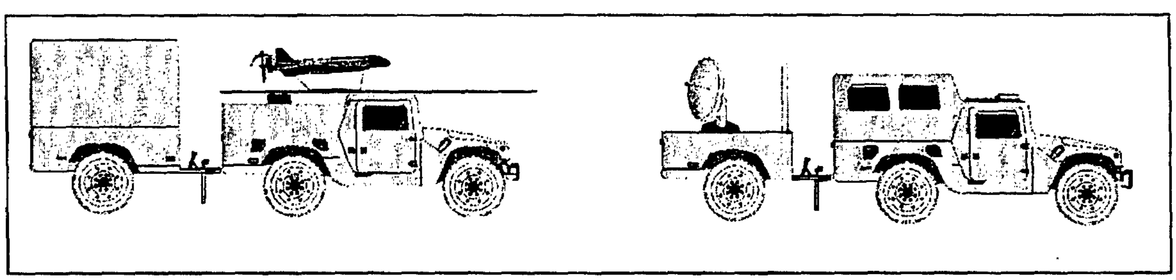

Figure 8 A TUAV System

UK Military Requirements for Unmanned Land Vehicle Combat Engineer Support

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Abstract

The paper describes the operational requirements and methods of achieving remote operation of Combat Engineer Equipments for use by the UK Army during periods immediately prior to combat, possibly during combat and extensively in post conflict clearance operations. The techniques could also be used in peace support or for non-military applications. Unmanned ground vehicles have several potential applications on the battlefield including reconnaissance, mine clearance and other engineer tasks.

The paper examines the teleoperational requirements for the adaptation of existing Combat Engineer Vehicles such as the Chieftain Armoured Vehicle Royal Engineer (CHAVRE), and the Combat Engineer Tractor (CET) and future requirements for service replacement vehicles such as Future Engineer Tank (FET) and Terrier (replacement CET). The benefits of the use of technologies to improve remote control equipment for the combat engineer are discussed with the evolutionary approach of developing vehicles which have greater intelligence, independence, versatility, and which reduce certain manpower tasks at favourable costs savings. The paper discusses specific topics on:- UK Engineer support requirements, direction of UK RLV programme, design philosophy, advantages and disadvantages of using UGVs instead of manned vehicles, safety features and some technology limitations.

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Introduction

DERA land systems department at Chertsey, Surrey, is currently conducting applied research in support of the UK Ministry of Defence (MoD) Operational Requirements branch (OR) for Combat Engr Equipments and Robotic Land Vehicles (ARMY) within the MoDs Applied Research Package 05 (ARP05). This work includes triservice , EOD and RCV's.

The paper describes the operational requirements and methods of achieving remote operation by remote teleoperation adaptation of existing Combat Engineer Vehicles. The Combat Engineer Equipments are for use by the UK Army during periods immediately prior to combat, possibly during combat and extensively in post conflict clearance operations. This is by definition a hazardous environment where operators could be under fire or at risk from a variety of unexploded ordnance. The remote control techniques can also be used in peace support where a variety of dangerous tasks need to be completed to render the area safe.

The engineer equipment programme is broad and includes about 140 projects which are split into various capability areas ranging through bridging, fortifications, mines and demolitions, countermine, explosive ordnance disposal (EOD) and water supply to name but a few. This research is used to assist in defining the requirements for new equipments and hence it eventually informs the procurement process carried out by the MoDPE (DPA by 1 April 99).

Unmanned ground vehicles will have certain applications on the battlefield, for example in reconnaissance, breaching, bridgelaying, obstacle construction and mine clearance. Certain tasks in specific scenarios can be extremely hazardous, hence the use of remote control will certainly reduce the danger to men in some of these situations. In this presentation, remote control using teleoperation is discussed using some examples of demonstrations already successfully carried out.Current technology can already enable manned vehicles to be converted to

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

remote operation for tasks where men would be particularly endangered. The introduction of unmanned ground vehicles (UGV) technology should therefore be evolutionary, with the aim of developing vehicles which have greater intelligence, independence and versatility, and which could save manpower preferably at reduced costs.

The idea of robots on the battlefield will conjure up to many, visions of large-walking creatures roaming free and destroying everything they encounter. Whilst the battlefield use of robots of such sophistication is still a long way off and may never be achieved without a man-in-the-loop to provide authoritative command, UGV's of more limited capability are already making an important contribution to the modern army. UGVs with man-in-the-loop control are now widely used for explosive ordnance disposal (EOD) tasks, and have been used in this role for over 20 years.

User Requirements

Over the years, the need for, and scope of, Engineer support on the battlefield has been well established. It is provided by a wide variety of equipment and vehicles, optimised for their specific role and place on the battlefield. Engineers have, and will continue to use, a number of armoured vehicles to provide mobility, counter mobility and survivability support to formations whilst providing protection to their own crews.

The current Chieftain Armoured Vehicle Launched Bridge (CHAVLB) and Chieftan Armoured Vehicle Royal Engineer (CHAVRE) were converted from Chieftain gun tanks in the 1970s and 1980s respectively, to replace their Centurion based predecessors. The Combat Engineer Tractor (CET) - see figure 1, and Engineer tanks all fulfil vital functions within Engineer regiments. It is planned to replace these vehicles in the next 9 years with the Future Engineer Tank (FET) with in-service date of 2004 and Terrier (replacement CET) in 2007/8 and will enable Engineers to provide improved close mobility support to armoured formations as well as carrying out other tasks. Tasks are undertaken throughout the width and depth of the area of operations, and are provided by a range of equipments with complementary characteristics and capabilities. Engineer mobility support tasks include wet and dry gap crossing, obstacle breaching, route opening, route maintenance, countermine and EOD battlefield clearance. Mobility is denied to an enemy through the enhancement of natural obstacles, the construction of man-made obstacles and the blocking of routes. The rapid ability to construct earthworks and defences for all-arms protection is an essential part of survivability support.

It is the aim that the Robotic Land Vehicles research programme will help to enhance the Royal Engineers and other arms capability by improving mobility and counter mobility support to Army armoured formations.

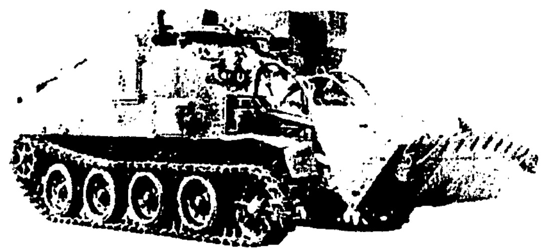

Figure 1 - Combat Engineer Tractor

Why Robotics?

It is probably as well to be clear as to why the military are interested in robotics. The reasons you see here are the main ones, although there may be others. Some advantages of using UGVs instead of manned vehicles are:

Maintaining the technological edge remains just as important as ever, so battle winning operational performance benefits will always remain the prime motivator. The importance of being able to minimise casualties on operations is now greater than in the past but with the acceptance of destruction of the unmanned vehicle. It is not necessarily due to any greater concern for human life, but because we no longer talk in the short term of wars of national survival, at least as far as the UK is concerned. There is the possibility of bolder concepts of operation, because of this reduced risk. Higher performance levels on extended and repetitive operations (where, for example, humans may suffer from fatigue, boredom or stress) and manpower reduction (as robotics compensate for a reduction in manpower without loss of effectiveness).

Conversely, there are disadvantages. Their high cost. A lack of user confidence, acceptance and an increased logistic burden. UGVs are probably less flexible and adaptable than men. Finance is a major driver and any efficiencies that robotics can offer will always be gratefully received.

Direction of UK Robotic Land Vehicle (RLV) programme through DERA

The aims of the robotics research within ARP05 is to provide advice on land robotic issues, maintain DERA's ability to provide such advice, assist in assessing the military worth of different concepts and provide solutions to Urgent Operational Requirements (UORs) and to promote knowledge of land robotics capabilities and its limitations.

In this area which does not attract a large amount of funding compared with for example the US, these aims ensure that amongst other things, the military, can retain an intelligent customer status and that the military OR and PE community are aware of the potential of robotics for future equipments.

Two of the equipment types discussed here today are where DERA have conducted research into teleoperation for remote driving and manipulative type engineer tasks. Other applications for other Engineer vehicles will be likely in the future including remote control of mine detection and mine neutralisation sensor carrying vehicles. The need for teleoperation techniques will most likely require colour and contain elements of mono or stereo vision, augmented reality, virtual reality (VR) or a combination. The programme has so far been concentrating on teleoperation kits for in-service vehicles such as the AVRE and the CET. It is seen as the most likely route for robotics to enter service and gain user acceptance. Acceptance of new technology equipments has always been a challenge to the researcher especially where safety is at risk. The growing requirement these days is to show that the benefits to the user outweighs the cost of development. We are currently investigating technologies that will improve teleoperation capabilities - these are stereo vision, optical flow, communications and image enhancement through augmented reality techniques.

Design Philosophy

The philosophy for the core area of the DERA RLV research programme has been to take the latest available technology and assess its capabilities against the Users requirement. Since UOR's occur from time to time, by assessing the latest technologies and equipments, rapid responses can be made when the need arises to provide appliqué kits for the UOR. The use of such kits allows flexibility where the kit can be removed reasonably quickly from the vehicle and it can then be interfaced with another type of vehicle with minimum of interfacing such as a PC flash disk, e.g. PCMCIA card. Commercial off the shelf equipments are used where ever possible. There must be no interference with the manual operation of the vehicle and a short change over time is required from manual to remote control by, for example switched operation. Design concepts must be space conscious as the controls and interface units must fit into already cramped spaces in the Engineer vehicles. Operator Control Units are required to be fitted into the secondary vehicle. Space is an important consideration and the use of Helmet Mounted Displays or VR systems may help to alleviate this problem. A recent enhancement of the research budget has allowed the programme to investigate future techniques such as novel vision and augmented reality for teleoperation.

Teleoperation kits for AVRE and CET

Appliqué kits for possible UOR use in Bosnia and also as proof of principle for future FET and Terrier programmes were investigated in 1995/96. The robotics remote control system currently being used in the US SARGE programme was purchased and minor modifications were made to suit the UK MoD requirement. using this equipment, the AVRE mineplough and fascine operations - see figure 2, were evaluated, by way of monovision teleoperation to drive the vehicle remotely and carry out the manipulative tasks. Ploughing up mines is an extremely hazardous task and any reduction in risk is welcome. The buried or surface mines can be in various forms from anti-personnel to the larger anti-tank types with explosive contents ranging from 2-10 kilograms. They may well also be booby trapped and liable to explode when approached, disturbed or interfered with. Depth ploughing is used for route clearance and surface clearance ploughs are also used to clear runways or roads of unwanted ordnance and minor obstacles. Remote teleoperation is of great benefit in these situations.

Fascines are bundles of rigid plastic pipes and are used for filling in ditches to enable them to be breached. They are also recoverable but in a combat situation may be left in place. Loading the fascines manually is quite difficult for one operator to complete the task. A selection of carefully positioned "remote" cameras can aid this but the task remains an arduous one. Deployment of the fascines is easier. The tank is driven into position and the restraining chains have to be released. The fascine platform is tilted from the rear and the fascines slide off forward. Up to 3 fascines can be fitted to each vehicle at a time.

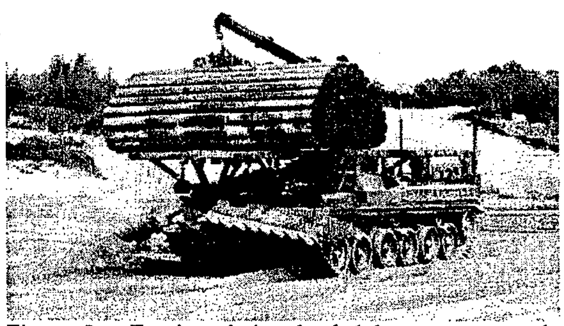

Figure 2 - Fascines being loaded by crane onto the AVRE

Teleoperation for CET has been based on the methodology and hardware used on AVRE. From the AVRE trials, driving functions were not difficult, thus the CET research was aimed at investigating and improving the manipulative tasks. Various trials have been conducted since 1997 with the main technical objective being to investigate digging tasks required in earth moving, the construction of obstacles such as sand banks and tank ditches. Clearance of obstacles was investigated such as filling in NATO standard tank ditches. Other clearance activities require the removal of heavy obstacles, for this, the CET 4-in-1 bucket is ideal for these manipulative type tasks, but not easy to implement because of limited visual perception.

Other reasons for consideration for teleoperation are, use by a single operator, advance selection of cameras and camera positions to enhance views and depth perception., the use of microwave link for a 1-2.5Km line of sight video transmission or relays to provide non line of sight vision to the remote command vehicle. A minimum of three cameras are fitted to the front of the vehicle and one at the rear. The centre front is mounted above the drivers head which improves forward vision by reducing obscuration by the ploughs and bucket. Two side cameras improve side/peripheral vision and allow accurate driving within narrow "safe lanes" or fenced off areas such as minefields or improved digging perception. The rear camera allows accurate and fast reverse driving. Operator control units can be fitted to display single or multi image options.

Operator Control Unit and its functions

The operator control unit (OCU) was selected for its history of performance use on the US SARGE programme. In the UK research programme, it was modified to perform driving and manipulative tasks and consists of a 486 33MHz PC with video LCD display and connections for interface outputs. Driving is via a motorbike handlebar control offering various functions such as steering, accelerator, braking and gear change. Control of the ploughing and fascine operations are done with the joystick. Other functions have been modified to provide the 4 in 1 bucket controls. The bucket can be operated by joystick or by standard bulldozer lever type controls to provide such functions as - raise/lower, digging/dumping, open/close and float/level grading.

Safety

The OCU PC is able to offer many diagnostic capabilities - for our purposes items such as, gear status, vehicle speed, low oil pressure warning, safety status warnings, communication link dropout etc. have been incorporated. Communications for remote links from the command vehicle to the remote vehicle offer control of the remote vehicle by two way radio link. The military vehicle radio, in the case of AVRE/CET is a VHF Clansman and was used to provide command functions such as engine control, steering, and braking. This technique is described in detail in the paper by Mr Peter Gibson.

Safety is paramount when remotely controlling the large vehicles. The computer hardware has a safety unit with watchdog/ command data safety flags. An in vehicle safety cut - off switch is also incorporated. This feature is essential when conducting evaluation trials, some of which do take place at the researcher's site. Some vehicles lose their hydraulic breaking when the engine is switched-off, an important point to remember when considering safety. The software is required to be fail-safe but not safety critical.

Technology limitations

One of the most complex technology areas is the communication link between the remote vehicle and its operator, particularly given the amount of information that needs to be transmitted. Autonomous vehicles, which can 'see' and 'think' for themselves and thus need little operator intervention and only intermittent communication are being considered for the future. However, given the current state of the art, it is realistic to assume that for the foreseeable future all UGVs on the battlefield will rely on visual information of some type being sent from the vehicle to the operator to allow man-in the-loop operations.

High resolution video contains a large amount of data and thus it's transmission over several kilometres in real time demands a large bandwidth. Image compression techniques are possible, but care must be taken to ensure that close to real time video is achieved. Fibre optic cables as the transmission medium for the video link offers real bandwidth advantages and is covert. They do however seriously impair vehicle manoeuvrability especially when reversing, and they are vulnerable to battle damage, accidental snagging and direct physical attack.

Ongoing and future work

Future areas of work at the robotics department at DERA to be covered are: -

Modelling for optimisation of operator perception and awareness, trials of stereo vision kits on the CET, assessment of head mounted displays and LCDs for stereo vision, use of inclinometers to judge slopes, the use of force feedback to "feel" driving and manipulation of the bucket, obscured vision driving, use of limited night vision equipment.

Co-ordination with other nations and groups -

USA - France - SILVER (UK- Industry/Academia special interest group for advanced robotics and intelligent automation). CLAWAR. EU Brite Euram thematic network on climbing and walking robots. The core activity of our research continues to be improvements to in-service vehicles through current and future technologies. It is anticipated that this will gradually change as the robotics trend is tending towards the field of semi-autonomy.

Concluding note

I believe that UGVs will become increasingly important in military applications for RLV tasks as they can be used on hazardous tasks without endangering men.

Reduced levels of manpower in the modern Army need to be compensated for by increased levels of technology if the same or greater level of operational effectiveness is to be achieved. Some repetitive and manpower-intensive tasks, such as convoying, logistic re-supply and security patrolling, could be carried out reliably by remote equipments and for longer periods, and would thus free people for other demanding tasks.

Bearing in mind events from around the world, it seems increasingly likely that the army of tomorrow will find itself involved more and more in operations other than war. Peacekeeping operations, with the intrinsic political unacceptability of loss of life, seems sure to promote the case for using teleoperated UGVs.

The UK sponsor for the UGV work is the Ministry of Defence, Main Building, Whitehall, London. I would like to thank Lieutenant Colonel Ian Blanks, SO1 Engineer, DDOR (Engr&NBC) for assistance in offering advice and material on User requirements.

Any views expressed are those of the author and do not necessarily represent those of the Department/Agency.

UK Experience with Unmanned Land Vehicles for Combat Engineer Applications

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Abstract

DERA is currently conducting applied research in support of the UK MOD programme for Combat Engineer Equipments which includes Robotic Land Vehicles.

Three examples of research into remote operation of combat engineer equipment are described, the Scatterable Mine Clearance Device (SMCD) on a 15 tonne truck, Chieftain Armoured Vehicle Royal Engineers (CHAVRE) with mine plough and fascines, and Combat Engineer Tractor (CET) fitted with 4-in-1 bucket. The paper addresses the advantages and limitations of operating via remote control and suggests techniques that alleviate some of these problems. All of the systems described used appliqué kits on in-service vehicles with no vehicle modifications and were intended to be capable of use in operational environments. Adaptation was achievable in less than a day and there was minimum interference with normal operation, change-over to remote control being near instantaneous. The presentation includes a short video clip of aspects such as tele-operation from moving vehicles, vision needs and problems encountered when undertaking specific tasks such as digging and obstacle negotiation. Results of our trials are summarized and pointers given to future research and features that should be incorporated in future systems. Mr. Peter Gibson - Robotics Technical Expert,
Defence Evaluation and Research Agency (DERA), Land Systems, Chobham Lane, Chertsey, Surrey, KT16 0EE, UK

Introduction

UK MoD has much experience with robot vehicles, including bomb disposal systems such as Wheelbarrow. The paper discusses three examples of full size vehicles that we have converted for remote operation. None of these has been used in military engagements though all were prepared with the potential for urgent operational requirements in mind. There is a considerable logistic burden associated with the deployment of a special remote control vehicle. Dedicated troops are needed and there are problems in getting vehicles to the right place in time to do a useful task. We have developed a philosophy of adaptation, which uses an appliqué kit to convert a conventional vehicle and allow remote operation, without undue interference to normal operation. It is envisaged that these kits would be made available in appropriate theatres of action and that vehicles would be pre-prepared to allow remote operation if the circumstances required it.

Driving Remotely In Following Truck (DRIFT)

The adoption of air or rocket deployed surface scattered mines and bomblets led to the investigation of a Scatterable Mine Clearance Device (SMCD), this is similar to a snow-plough and sweeps the road surface clear of sub-munitions. This task is very hazardous when the plough is attached to a logistic vehicle. We were asked to devise a simple tele-operation scheme that would remove the driver from the immediate danger zone. As convoys are in continuous motion it is necessary to find somewhere to put the driver, we chose the passenger seat of the following vehicle.

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

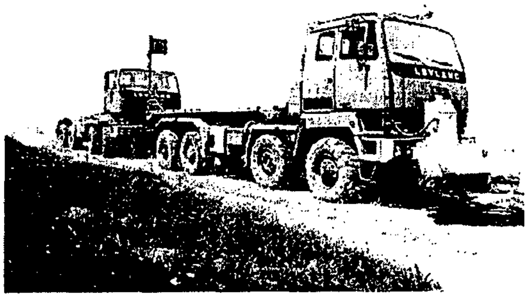

FIG 1 - DRIFT tele-operated Truck

Teleoperation controls are fitted in the following vehicle. These include steering wheel, pedals and a video screen giving the remote operator familiar controls to work with. The lead vehicle is fitted with a temporary pedal actuation frame (similar to dual controls for driver instruction), and a steering wheel servo. These do not prevent conventional operation of the controls (though the steering servo is removable for normal use).

FIG 2 - Control Actuators

Communication is by means of a wire tether fitted to a constant tension reeling system. This avoids the need for slip-rings and gives up to 30 metres vehicle separation. Open loop control was chosen for all driver inputs, with a local position servo on the steering wheel. Compressed air was used to control throttle and brakes with electricity for steering and SMCD controls. A wide-angle camera mounted above the windscreen feeding back over the cable link to the operator's screen provides vision. It is possible to view the truck directly if required. Tele-operation is straightforward when the rear vehicle is stationary; the controls are conventional though lacking in feel and the multi-turn steering damps the control input. Motion cues from the following vehicle can be falsely interpreted as tele-operation feedback; this illusion can be powerful though inappropriate responses can be avoided with training.

Armoured Vehicle Royal Engineers

AVRE is a main battle tank chassis equipped with overhead platforms for ditch filling fascines (bundles of plastic pipes) and the vehicle has the normal mounting for the mine plough. This vehicle can be used in hazardous areas such as when breaching a minefield under enemy fire. We were tasked with making a tele-operation kit that would enable rapid (less than one day) adaptation with near full functionality of the Chieftain version (CHAVRE) to include minefield breaching and gap filling with fascines.

FIG 3 - AVRE with mineplough

Remote control is by data at 4.8k Baud rate and modulated onto a voice channel of the standard combat radio. To ease multipath problems, two switchable antennas are used, one positioned out of phase with the other. The single one way video-link from the remote vehicle to the command vehicle has its input switched according to the camera selected. We use a 1.3GHz FM commercial microwave links (Gigawave Antennas UK) with circular polarized antenna to avoid multi-path interference as the vehicle moves. This equipment was developed for Formula 1 in-car video for TV broadcasts. Radio communication generally requires line of sight communication to transmit these high bandwidth video images though fibre optic links, which offer even higher bandwidth, can be used if the vulnerability of a tether can be tolerated.

The control data contains embedded safety codewords that are decoded by hardware at the remote vehicle and used to enable all safety critical vehicle and weapon systems. Two independent methods were used to avoid the chance of a single mode failure. Software was deemed to be not safety critical and allowed the use of high level languages even though they could not be verified error free. Military Ordnance Board approval was needed and given for this application due to the use of explosive bolts to release the fascines.

The appliqué kit philosophy was followed with "Y" pieces interconnecting the standard wiring harness to the control system. Hydraulic power from the vehicle power brakes was used to apply the steering and brakes (non proportional – on/off) with a servo pressing on the throttle pedal linkage and gear selection and other functions carried out by directly energising the wiring harness. This was arranged to be transparent to the normal crew though there is a safety switch to disable the remote operation when not wanted. Several video cameras were provided; normal driver's view, wide angle view over the plough, reversing and wing mounted manoeuvre cameras. All the electrical equipment was mounted in an area vacated by the crew's storage compartment.

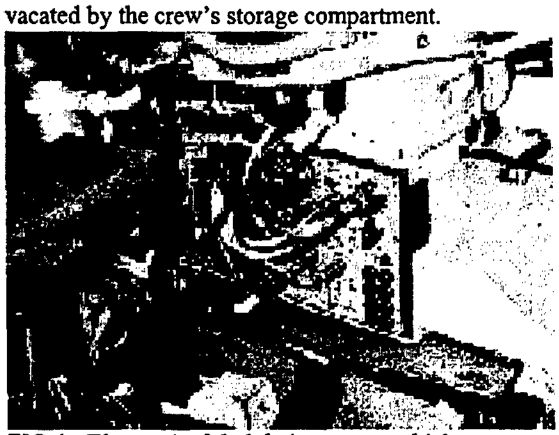

FIG 4 - Electronics Module in remote vehicle

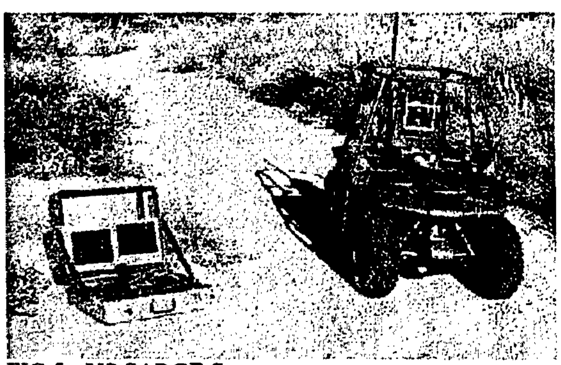

FIG 5 - US SARGE System

The operator console was a suitcase based PC, derived from the US Sarge remote control programme, with touch screen for command menu and flat screen for video. Audio feedback and data throughput measures were provided. Message counts on command and tell-back data were displayed and gave a measure of the robustness of the communications links. It was found necessary to use short data words in noisy environments to avoid all signals being rejected as corrupt. Rates of 20 messages per second represented perfect conditions, values below 10 showed that half were being lost and some action should be taken to avoid being cut-off. In most cases the video degraded quicker than the command and it was possible to drive out of bad reception areas. The safety circuits would prevent operation if command messages were not received within one second of each other.

Trials

Trials were carried out using an experienced military crew who very quickly became familiar with the functions and were operating at full speed. They claimed that it was better than normal due to the improved viewpoints made possible by the freedom in positioning the cameras, and the lack of motion due to not being in the vehicle! On most occasions a safety driver was carried though all armoured hatches had to be shut when live explosive bolts were in place. An interesting point is that although there was a remote engine start there was no remote stop facility, as engine power is needed to ensure brake pressure supply. Several runs were carried out without a safety driver on board; a safety procedure was needed to ensure that the vehicle could not move when live crew are approaching. Operation of this vehicle was quite undramatic; in fact it was impossible to tell from external viewing if the vehicle was under remote or manual control.

The same appliqué kit was used to provide an unmanned target tank for missile trials (a Chieftain tank scrapped as part of the arms limitation treaty). This was operated at 2Km range on Salisbury Plain and suffered 19 encounters with Swingfire wire guided missiles. Although dummies, the warheads caused considerable damage due to explosives and unspent propellant and it was fortunate that we managed to keep the target mobile through the trial. A latter night trial against TRIGAT missiles was also successful with no hold-ups due to target malfunction. This work stretched the capabilities of the video and command links and confirmed the graceful degradation of the system.

Combat Engineer Tractor

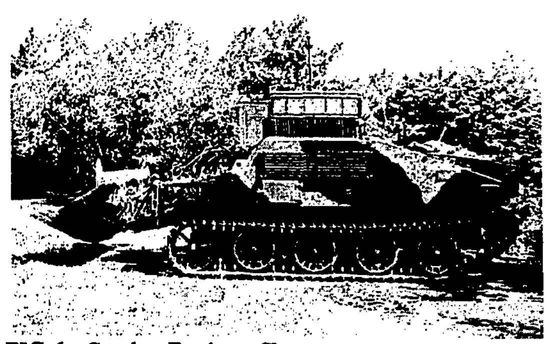

FIG 6 - Combat Engineer Tractor

CET is a high-speed lightly armoured shovel/loader designed to prepare earthworks. We were again asked to demonstrate a simple adaptation for remote operation though the conversion time constraints were less severe than we had imposed on ourselves for the first two examples. We followed a minimalist approach interacting with the vehicle controls in the simplest way practical. All controls except throttle were on/off with additional hydraulic valves bypassing the manual controls to provide the digging functions. The valves and hoses fitted were rated for ½ the flow rate to minimise the added bulk (continuous digging was not anticipated). Electronic control was similar to the AVRE example described earlier with minor modifications to accommodate stereo vision and the bucket controls. It was found that tele-operated driving presented no unexpected problems but it was difficult to sense the shape of terrain features during earth moving, this resulted in inaccurate excavations and higher risks when breaching anti-tank ditches. This indicates that more 3D cues may be needed for slow moving duties such as digging where features may be difficult to recognize.

Discussion

Vision seems to be the key feature in adapting conventional military vehicles to remote control. Lack of control finesse did not cause problems even though we did not use proportional valves or similar servo control techniques when we believed on/off control might work. Military vehicles are designed to tolerate a degree of abuse especially in these hazardous environments. CET braking was somewhat abrupt and uncomfortable for the safety driver but did not cause control problems. Visibility from conventional manned vehicles is highly compromised when "closed down" with all the armoured hatches shut. Forward vision is very limited for AVRE fitted with mineplough and there was a noticeable reluctance to demonstrate digging closed down in CET. Tele-awareness suffers with remote operation and it may be that this degradation makes some tasks fall below the "do-able" borderline without special attention to operator needs. Priority should be given to appropriate views for the task in hand; this is quite easy with multiple video cameras. Devices such as laser rangefinding systems might help understanding of the environment but care would be needed to present this to the operator in a meaningful way.

Conclusions

The three vehicle adaptation systems described were useable, reliable and did not interfere with normal operation. The simple technology used to make the systems affordable did not cause problems, visual resolution appeared to be the technology limitation to performance. Image flow helps make sense of the video and driving at speed is not difficult, a wide field of view aids tele-presence but makes distant objects difficult to see. The workload can be high, especially for an unassisted novice operator and there would seem to be reason to consider a two-man team with both command and driving functions.

A short video is shown at the conference depicting driving and ploughing of the remote AVRE by tele-operation and shows the difficulties associated with CET remote obstacle clearance tasks.

Controlling Unmanned Vehicles: the Human Factors Solution

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Abstract

Recent developments and experiences have proven the usefulness and potential of Unmanned Vehicles (UVs). Emerging technologies enable new missions, broadening the applicability of UVs from simple remote spies towards unmanned combat vehicles carrying lethal weapons. However, despite the emerging technology, unmanned does not implicate that there is no operator involved. Humans still excel in certain tasks, e.g. tasks requiring high flexibility or tasks that involve pattern perception, and decision making.

An important subsystem in which the technology driven aspects and the human factors driven aspects of UVs meet is in the data–link between the remote vehicle and the operator. The human factors engineer wants to optimize operator performance, which may require a data–link with an extremely large capacity, while other design criteria typically limit the bandwidth (e.g. to lower costs, or because no more bandwidth is available in certain situations). This field of tension is the subject of the present paper.

The paper describes two human factors approaches that may help to resolve this field of tension. The first approach is to reduce data–link requirements (without affecting operator performance) by presenting task–critical information only. Omitting information that is not needed by the operator to perform the task frees capacity. The second approach is to optimize performance by developing advanced interface designs which present task–critical information without additional claims on the data–link. An example will be given of both approaches.

1 Introduction

Nowadays, Unmanned Vehicles (UVs) come in different kinds and forms (see Figures 1 and 2). The last decade, UVs have shown that they have the potential to play an increasingly important role on the future battlefields. For example, in the next decades, an increasing transition from air based cockpits to ground based cockpits for use with man-in-the-loop UAVs is foreseen.

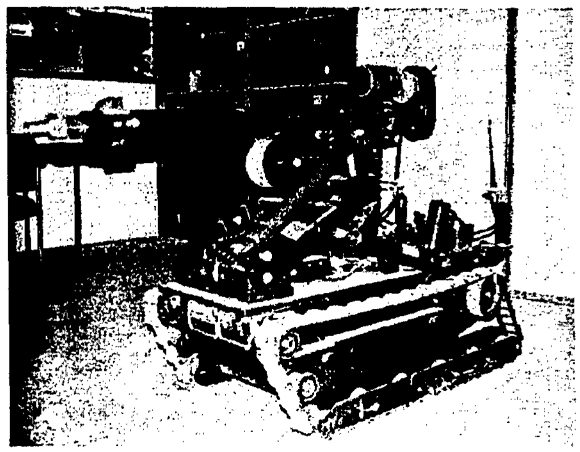

Figure 1. Example of an Unmanned Ground Vehicle for ordnance disposal as in use by the Royal Netherlands Airforce.

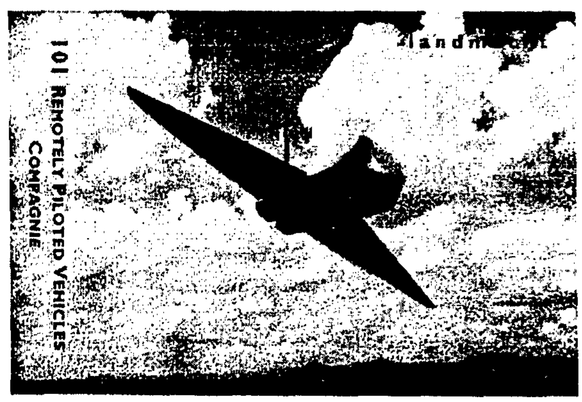

Figure 2. Example of an Unmanned Aerial Vehicle, to be delivered to the Royal Netherlands Army during 1999.

The primary advantage of UVs is the reduced risk of casualties and losses of personnel. In the light of the changing role of NATO with more emphasis on humanitarian and peace keeping operations, UVs can also help preventing the loss of the public support. Furthermore, UVs are better suited for dull or dangerous tasks (e.g. long–endurance missions and

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

missions in NBC contaminated areas), and UVs may be much cheaper than their inhabited counterparts.

Emerging technologies enable new missions, broadening the applicability of UVs from simple remote spies towards unmanned combat vehicles carrying lethal weapons. However, despite the emerging technology, unmanned does not implicate that there is no operator involved. Humans still excel in certain tasks, e.g. tasks requiring high flexibility or tasks that involve pattern perception, and decision making, and humans are certainly required in the case of weapon delivery. Typical tasks that are allocated to the human operator include: mission planning, interpreting images from the remote location, decision making and weapon delivery. This means that system performance both depends on technological developments and on human factors considerations. More strongly, it may be stated that the human–in–the–loop is critical for mission completion.

System integration

Human factors knowledge may be required for different aspects of the system design. Questions and aspects that involve human factors considerations include: task–analysis (which tasks are allocated to the machine, and which to the operator), the number of vehicles one operator can control, interface design, workload, team performance, and selection and training of personnel. An important subsystem in which the human factors aspects and hard and software technology converge is in the data–link between the remote vehicle and the operator. At the same time, this subsystem embodies the field of tension between human factors requirements and other design considerations. For example, dynamic tasks like steering and orientation tasks, typically require a steady stream of images. Optimizing operator performance for these kind of tasks may result in a data–link with an extremely large capacity. On the other hand, other design criteria force to limit the bandwidth capacity (e.g. to lower costs, or because no more bandwidth is available in certain situations). This field of tension is the subject of the present paper.

The paper describes two human factors approaches that may help to resolve this field of tension. The first approach is to reduce data–link requirements by presenting task–critical information only, and therefore omit information that is not needed by the operator to perform the task, but unnecessarily uses data–link capacity. The second approach is to optimize performance by developing advanced interface designs which present task–critical information without additional claims on the data–link. An example will be given of both approaches. In driving unmanned ground vehicles via a camera–monitor system, careful consideration of image parameter values can reduce the required data–link capacity considerably to normal video images. In applying advanced interface designs in controlling the on–board camera of a UAV, operator performance can be improved without enlarging the data–link capacity. Both methods may help to reduce the data–link capacity without compromising on operator (and system) performance.

2 Effects of the tele–operation environment on operator performance

By employing a UV, one of the goals is to combine the remoteness of the environment with some form of human intelligence (otherwise one could for example employ an unguided missile). The ultimate goal is that the operator can act and perform as if he or she was really present at the remote location (or even better), e.g. the camera operator of a UAV must be able to search and identify objects as if he or she was actually flying above the terrain of interest. However, one of the larger obstacles on this road is the sensory deprivation inherent to a tele–operation situation. The operator is not present in the remote vehicle and has no direct sensory contact with the remote environment. Ergo, sensory information must be mediated with the help of on–board sensors. The inherent information degradation may negatively affect operator performance.

Below, some examples are given of degraded or lacking information and the possible consequences. A more detailed picture regarding remote camera control is sketched in Section 4.1.

1. The most important source of information from the remote environment is usually the image of an on–board camera. It is not common to provide other forms of sensory information, such as forces in controls when turning a curve, auditory information on forward speed, and proprioceptive information on vehicle swaying. This (redundant) information may enhance performance on tasks like speed estimation, and

controlling lateral acceleration.

2. Furthermore, the visual information that is provided will be of a degraded quantity (e.g. reduced spatial resolution, field size, and colour) compared to direct viewing. This will directly affect performance on detection and identification tasks, and may also lead to disorientation of the operator.
3. Data–link restrictions will further degrade the available visual information. This may, amongst other things, result in low update rates of the images. When the refresh rate becomes lower, and the presentation becomes snap–shot like, performance on tracking, steering, and orientation tasks will be directly affected.
4. Finally, in the tele–operation environment, the control devices may provide less information. An example is joystick camera control which will omit the use of the high quality information from neck and eye muscles on viewing direction which are available when an observer is situated inside a helicopter and uses a pair of binoculars.

Tasks that are especially affected by degraded sensory information are orientation and manual control tasks. Although getting the operator out of the loop (e.g. employ automated line scanning, or target tracking) may seem to solve this problem, it does not automatically improve system performance. First, by introducing automation, the role and tasks allocated to the operator change, and this is often not a change for the better, because:

1. The operator ends up with tasks that can not be automated (which doesn't mean that the operator is good at it),
2. The operator's role changes from manual to supervisory control, which will induce new kinds of failures (failure to monitor, vigilance decrement, over reliance on standard values, automation–induced complacency, increased latency in detecting problems etc.),
3. Operators may be frustrated by having to watch an automate performing a task, while they are not able to intervene (e.g. operators will certainly want to intervene when a remote camera scans the environment, and the operator detects something of interest).

Second, there are situations in which manual control modes are favoured over automation or a fully autonomous vehicle. For example:

1. Manual camera control enables optimal use of human expertise concerning information gathering tasks (e.g. to recognise and interpret details of weapon systems, and to use knowledge of common lay–outs of convoys).
2. The technology for tasks as automatic target tracking and recognition may be insufficient. It is believed that target motion may not be sufficiently predictable to warrant human tracking (Eisen & Passenier, 1991a,b). Detection and identification of unwilling objects in video–images still can't be reliably automated, although operator cueing might be possible.
3. Even in automated processes, it may be expected that operator intervention will occur, e.g. in order to influence the target–search pattern (Moody &Thompson, 1989), to avoid boredom, or to maintain situational awareness (Tirre, 1998).
4. The technology to automatically drive a ground vehicle in unknown (off-the-road) terrain is insufficient for driving with high speed. The human operator excels in obstacle avoidance and path finding.
5. Both takeoff and landing are sometimes accomplished manually with a camera mounted in the vehicle's nose (e.g. Predator UAV).

3 Reducing data–link capacity by omitting non–critical information

An important contribution of the human factors engineer is determining task–critical information. Figure 3 shows the rationale behind this approach. The graph shows typical results found in human factors research. Lowering a specific system parameter (e.g. the update rate, colour depth, or spatial resolution of the images of the remote environment), will result in a slow decrease of operator performance until a specific level (marked by the arrow in the graph). When the level of the parameter is lowered below this level, performance will suddenly drop. In the example depicted in the graph, the system parameter (and therewith the data–link capacity) may be halved, resulting in only a small performance decline.

For all kinds of tasks and environments, this procedure may result in data–link reductions without performance loss. An example is given for the manual control of an uninhabited ground vehicle (UGV), in which the driver steers and navigates through the remote environment on mediated images from an on–board camera. The next Section gives an overview of the most important image parameters, and their optimal value in the field of tension between operator performance and data–link capacity.

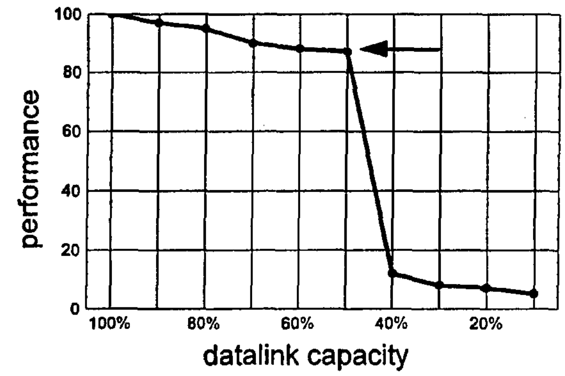

Figure 3. Illustration of omitting non–critical information. Performance decline is not linearly related to data–link capacity.

3.1 task–critical information in UGV control

To fully employ the human skill to safely drive a vehicle with high speed through unknown terrain, manual control may be preferred over fully autonomous. However, this operator task is far more difficult than normal driving. The perceptual input for the operator is usually restricted to mediated images from an on–board camera, no force, auditive, or proprioceptive information on vehicle behaviour and speed is available. Furthermore, the visual information that is available is of degraded quantity compared to normal driving (e.g. reduced spatial resolution).

The required quality of the mediated information on one hand and the need to restrict the data–link capacity on the other, ask for a careful consideration of image parameters. The goal must be to come to operational requirements for the most economic man–machine–interface without hampering operator performance and vehicle usability.

Based on studies on driving behaviour, literature reviews, and pilot studies, the critical image parameters can be identified. These parameters were studied in different research projects and experiments at TNO. The overview and recommendations given below are based on field and simulator studies.

The following image parameters can be critical in vehicle control:

- **Field size**: the field size is directly related to the needed data–link capacity (when the relative resolution is constant). Normally speaking, the field size of the images will be considerable smaller than the field size of normal drivers (more than 140° horizontal field of view). If the field size is lowered, the operator will experience the remote world as looking through a tube. Smaller field sizes will hamper the use of peripheral vision, and may hamper the perception of speed, orientation capability, and other tasks. Research has shown that a minimum field size of 50° diagonal is required, while 100° is preferable (Van Erp & Padmos, 1998). It is recommended to consider enlarging the horizontal field of view (FOV) at the expense of the vertical FOV for driving on flat terrain.

- **Magnification factor**: employing a magnification factor smaller than 1.0 may be advantageous to enlarge the field of view. However, these magnification factors will result in biases in the perception of speed and distances, and in less object motion on the display. The latter may degrade performance, e.g. enlarge the course instability. Swaying of the vehicle will result in smaller object motion on the display, and is therefore harder to control. Moreover, the operator has no vestibular information to detect vehicle swaying! (Van Erp & Padmos, 1996).

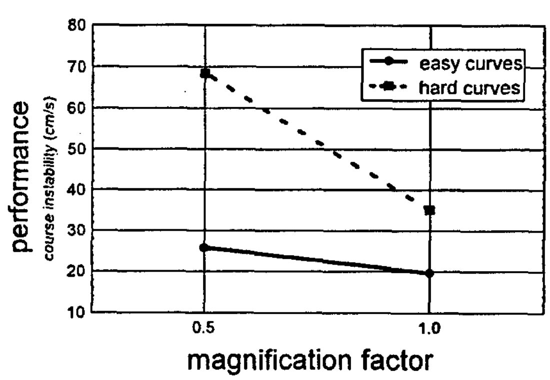

Figure 4. Example of performance degradation with magnification factors smaller than 1.0 which is especially present in critical tasks.

Figure 4 shows a typical example of the effect of magnification factor on the course instability in taking curves (Van Erp, 1995). Especially in critical tasks, magnification will degrade performance (in this example, the course instability doubles with a magnification factor of 0.5). Concluding: magnification factors less than 1.0 must be avoided, they are disastrous for driving performance, especially because the operator has no mechanical motion information.

• **Black and white vs. colour** images: for driving on paved terrain, black and white images are sufficient. However for driving in rough terrain, the estimation of ditches and other terrain characteristics is essential for good driving. Experienced drivers report that they partly rely on colour information (Van Erp, Van den Dobbelsteen & Padmos, 1998). The importance of this cue increases when there are no stereoscopic depth cues, and when image quality becomes less.

• **Update rate**: update rate is a very important parameter. Lowering the image update rate is a very easy way to reduce the data-link capacity. However, low update rates will hamper the perception of motion, speed, and heading, and may degrade the situation awareness of the operator. Especially in dynamic tasks, operator performance will be affected by lowering the update rate. Figures 5 and 6 give examples of the effect of update rate on driving performance in dynamic tasks. Critical update rates are 10 and 5 Hz for turning curves and a lane–change task respectively. In non–dynamic tasks (e.g. the estimation of distance), update rates may be lower. Typical experimental results show that the minimum required update rate is strongly task dependent, and ranges between 3 Hz to 10 Hz (Van Erp, 1996).

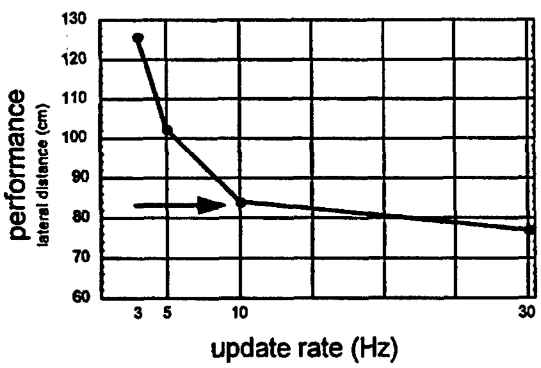

Figure 5. Effect of lowering the update rate on operator performance in turning curves. Critical update rate for this task is 10 Hz.

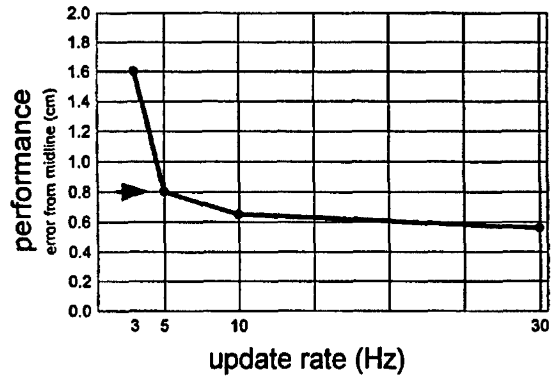

Figure 6. Effect of lowering the update rate on operator performance in a lane–change task. Critical update rate for this task is 5 Hz.

• **Spatial resolution**: the spatial resolution of an indirect viewing system will always be lower than that of the human eye (e.g. the resolving power of a 50°diagonal PAL image is about 0.5 $arcmin^{-1}$, in direct view, an acuity of 2 $arcmin^{-1}$ is not uncommon, Van Erp & Padmos, 1994). Spatial resolution is probably very important in driving through rough terrain, in which the perception of terrain characteristics is very important. However, for driving on flat, paved terrain, the spatial resolution may be highly reduced. For example Van Erp (1996) found no performance degradation for turning curves with a spatial resolution as low as 64×60 pix. for a 80°×60° H×V field size. For driving in terrain, the resolution must be at least twenty times larger.

• **Monoscopic vs. stereoscopic** viewing: for driving on flat or paved terrain, monoscopic viewing is sufficient. However, although stereoscopic depth cues are only profitable up till about 10 m., taking ditches and obstacles are tasks in which the absence of stereo vision will hamper performance, especially when the visual information is already degraded. This is illustrated in Figure 7, in which chauffeurs drove an armoured vehicle over a course with larger and smaller ditches. Different visual conditions were employed: direct view, in which the driver was only wearing field size restricting goggles, and indirect viewing with the same field size. In both visual conditions, the drivers performed the task with mono and stereo vision. The figure shows that the positive effect is apparent under indirect (degraded) visual conditions (Van Erp & Van Winsum, 1999).

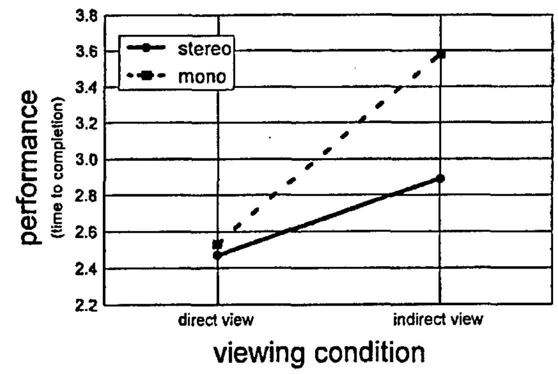

Figure 7. Effect of stereoscopic depth cues on driving performance in rough terrain. The positive effect of stereoscopic cues increases under degraded visual conditions.

- **Fixed vs. variable viewing direction**: a variable viewing direction (e.g. implemented with a pan and tilt camera, or by using different cameras with a fixed viewing direction), gives the operator a large field of regard with a small instantaneous field of view. However, a disadvantage of a variable viewing direction is that operators have difficulties in determining the viewing direction of the camera, and the heading direction of the vehicle. Different remedies can be introduced to reduce this disorientation, of which the strongest is to provide adequate vehicle references, that indicate the viewing direction compared to the vehicle. An other possibility is to make the viewing direction head–slaved, which gives the operator intuitive information on viewing direction (Van Erp & Kappé, 1997). This latter method, however, is very susceptible to factors as time delays in the data–link, and overshoot of the platform.

- **Placement and aiming** of the camera: make sure that the camera image contains a part of the vehicle. The availability of vehicle references enhances both driving performance and situational awareness (Padmos & Van Erp, 1996).

3.2 Conclusions

Given a specific data–link capacity, operator performance can be optimized by giving the operator the possibility to:

1. manually tune the update rate and spatial resolution required to perform the task,
2. reduce the vertical field size for driving on flat terrain,
3. choose for black and white images and monoscopic viewing for driving on paved terrain.

Further optimization may be accomplished by introducing head–slaved camera control with a limited instantaneous FOV. The above example shows that system performance may be enlarged by carefully choosing what information the restricted data–link is used for.

4 Reducing data–link capacity by applying advanced interface design techniques

To optimally employ the human expertise in remote camera control tasks such as target detection and identification, battle damage assessment, and the gathering of intelligence information, image analysts must preferably be able to manually control the on–board camera. This section discusses the second approach to enlarge system performance without additional claims on the data–link capacity: employing advanced interface designs. The possibilities of this approach will be discussed for an other task environment, namely remote camera control.

Remote camera control is much more difficult than looking to the outside world with a pair of binoculars. The first paragraphs will introduce the possible problems in remote camera control and the possible consequences for the operator. In the following sections, four examples are given of advanced interface designs that reduce the consequences of specific interface characteristics that are of primary concern in the design of UAV systems, including: field size, zoom factor, update rate, transmission delays, and lack of proprioceptive information on viewing direction.

4.1 Possible problems in remote camera control

In remote camera control, the operator views the world through mediated camera images. Amongst other things, data–link restrictions will engender camera images that are of less quality compared to images perceived directly by the human eye. Furthermore, the following shortcomings are typical in remote camera control (Van Erp & Van Breda, 1999):

- There is no proprioceptive feedback provided in the controls. In manual control mode, for instance in a situation that the camera is controlled by means of a joystick, the control will not give feedback on camera behaviour whatsoever;

- There is no vestibular feedback on vehicle attitude. Because the operator is not seated in the vehicle, vestibular information on vehicle behaviour (e.g. rotations) is missing. This means that the operator has no relevant information on changes in flying direction;
- There is no proprioceptive feedback on viewing direction. When the observer is situated on-board a vehicle, proprioceptive information of muscles in neck and eyes provides exact information on the viewing direction. In a tele-operation setting, where visual information is presented on a fixed monitor, this information is missing;
- There is no direct feedback on control input. When the operator produces an input signal, the result of this action will not directly be available. Delayed feedback may seriously degrade manual control performance, ultimately leading to a go-and-wait strategy (bang-bang control, overshoot) when time delays are considerable;
- Limited spatial resolution of the camera images. This is a crucial parameter in all camera control tasks (predominantly in detection and identification tasks). Enlarging the limited resolution per degree of visual angle by reducing the field size will also hamper operator performance (see below).
- A limited geometrical field of view (GFOV). A small GFOV may have several consequences. Firstly, the size of the GFOV is directly related to the required camera motion to scan a given area. Secondly, smaller field sizes will hamper the spatial integration of objects in the remote environment, will inhibit building up situational awareness, may lead to operator disorientation (especially since the sensor slewing will be relatively quickly (Carver, 1987)), and complicates the task of keeping track which areas are already searched (Carver, 1988), and where threat areas lie. Thirdly, if the operator chooses to manually slew the sensor, the workload is expected to increase as the GFOV decreases. And finally, in tracking tasks, the motion of a target relatively to the monitor screen will increase, which will decrease tracking performance (Poulton, 1974).
- A zoomed-in camera image. The limited field size, the limited resolution, and the minimum stand-off distance combined will force the operator to zoom-in on targets. Because a zoomed-in camera image disturbs the normal relation between camera rotation and translational flow in the camera image, this may be an important factor in operator disorientation. When based on the translational flow, the camera rotation will be overestimated.
- Limited update rate of the image. Lower update rates of the camera image will mainly affect dynamic tasks. Update rates below 10 Hz will decay the perception of the motion of the target, and of the camera and the platform. Very low update rates will lead to a snapshot like presentation of images, without any perceptual information on motion.

Concluding, sensory information on the remote environment may be lacking, or may be of lower quality as compared to the situation in which the operator is located inside the vehicle. The possible consequences on operator performance are described in the next Section.

4.2 Possible consequences on operator performance

Prioritizing the above list, the important bottlenecks for manual-camera control are the quality of the visual information from the remote environment, and the lacking of (proprioceptive) cues on camera viewing direction. Significant consequences for the operator are poor tracking performance (resulting in large tracking errors, and losing the target), difficulties in assessing camera, platform, and target motions, confusion on the flying direction of the platform, confusion on the viewing direction of the camera, disorientation, and degraded situational awareness.

4.3 Reducing low update rate consequences

The focus of this example is on improving camera control under low update rate conditions. The underlying study (Van Erp, Korteling & Kappé, 1995) included two experiments in which the operator of a UAV camera is supported by synthetic visual motion information. On the basis of knowledge about the present position and orientation of UAV and camera, system characteristics, and control inputs, an artificial grid of perpendicular lines can be presented over the camera image (a graphical overlay) that specifies the various components of UAV and camera motion (see Figure 8). This means that when the camera image is refreshed with lower update frequencies, the perpendicular lines move relative to a static camera image.

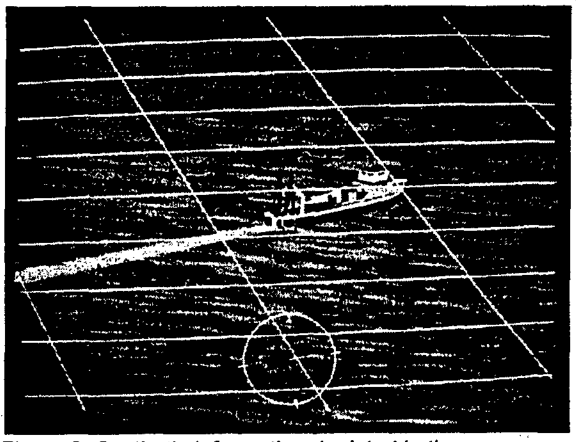

Figure 8. Synthetic information depicted in the camera image provide high quality motion information despite the update rate of the camera image.

It was expected that this (fast updated) synthetic image augmentation would help the operator in perceiving movements of UAV and camera, and therefore that it would improve the tracking and orientation performance of the operator. This hypothesis was tested in two experiments. In the first experiment subjects had to track a moving target ship from a moving platform, which meant compensating for translations and rotations of both the ship and the UAV. The results showed a significant positive effect of synthetic image augmentation (up till a factor 2). This effect became stronger in the conditions with low update frequencies (see Figure 9).

The second experiment involved a situational awareness task. After imposed translations and rotations of the UAV and camera during 15 s, the subjects' task was to point the camera at the position of a previously depicted target ship. This experiment too showed a significant positive effect of synthetic image augmentation on performance, which increased in the conditions with lower update frequency. This indicated that mutual positional relations were better memorized in the presence of the graphical overlay and, thus, that relative situational awareness was improved.

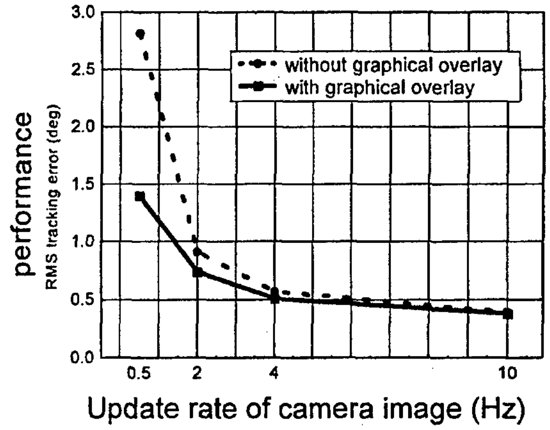

Figure 9. The positive effect of the graphical overlay increases with lower update rates.

4.4 reducing degradation of SA caused by zoomed–in images

The second example concerns an 3D graphical interface to improve situational awareness. A computer generated world (CGW) over and around the camera image was developed (see Figure 10), in order to counteract the disorientation caused by zoomed–in camera images (a comparable situation is present when people lower their pair of binoculars to re–orientate themselves).

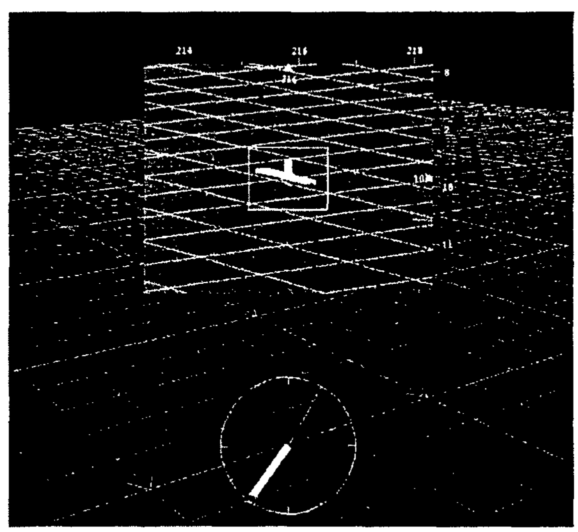

Figure 10. Simulated camera image with moving tapers, the quantitative indicators below the camera image, and the perceptually correct computer generated grid depicted over and around the camera image.

This CGW was perceptually correct, in that it resembled the view on the world from the UAV as if the operator was on-board (Van Erp, Kappé & Korteling, 1996). The results from the experiment substantiated the effectiveness of the CGW in improving the operators search performance: the search time and the total camera motions were significantly reduced when the CGW was presented (see Figure 11). Thus the CGW can counterpart the negative effects of a zoomed–in camera image and subsequently improves situational awareness. Supporting the operator by means of quantitative indicators, depicting camera heading and pitch, did not show any significant improvements in performance.

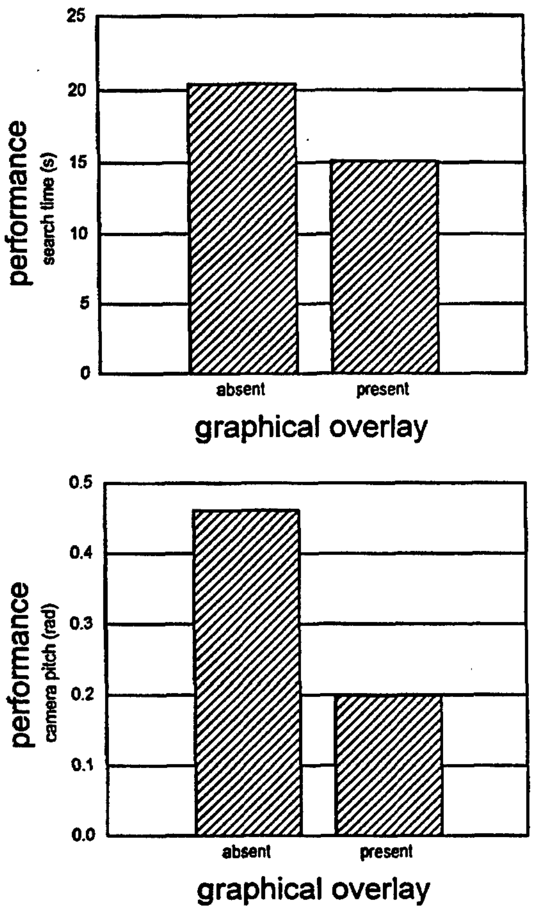

Figure 11. The positive effect of the graphical overlay is present on different objective performance measures.

The information provided by the CGW is fundamentally different from the information provided by the indicators. Gibson (1950) assumes that the information such as provided by the CGW may be picked up directly by the visual system, without demanding substantial visual attention. Therefore, the term ecological display was introduced for this type of displays. The more traditional (non ecological) methods of operator support all require the operator to use some kind of cognitive strategy to infer the UAV attitude from the presented (abstract) information.

4.5 Path prediction to counteract time delays

Another factor that may seriously degrade operator performance in UAV control is a time delay between control inputs and subsequent feedback about these inputs to the operator. Figure 12 gives an example of a radar display that includes a prediction of the camera footprint motion. The same technique may be used for electronic maps.

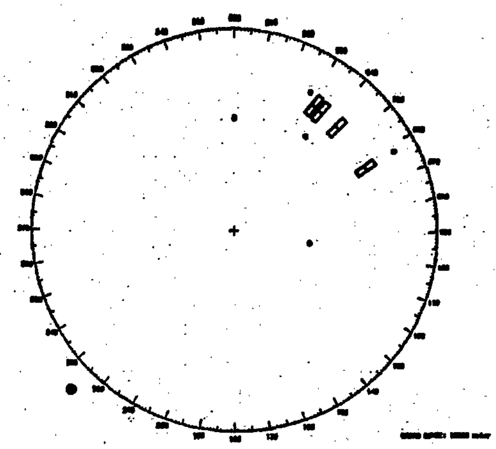

Figure 12. Simulated radar image with footprint prediction. The footprint prediction moves in real time, and indicates the location of the images to come.

Results of search task experiments showed that operator performance decreased when the update frequency is below 2 Hz, or when the time delay is larger than 2 s (Van Erp & Kappé, 1998). The presentation of a predictor led to better performance (see Figure 13), although it could not fully prevent performance degradation at 0.5 Hz update frequency.

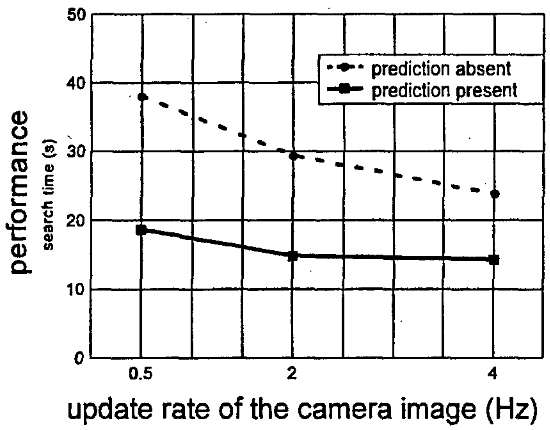

Figure 13. Footprint prediction has a positive effect on operator performance, and makes performance less dependent on update rate.

4.6 Head–coupled camera control

Head–coupled camera control may be a very intuitive way to control the remote camera. Enabling the operator to use high quality (proprioceptive) information on (changes in) viewing direction by introducing a head slaved camera system with a head slaved display (Head Mounted Display or HMD) may improve SA, compared to using a joystick and a fixed monitor. In addition, slaving the camera to the operator's head may benefit performance by reducing cognitive processing; changes in viewing direction do not need to be translated into motor commands for the hand. However, head slaved systems have drawbacks as well, e.g. the weight of the helmet changes eye–head co-ordination may be uncomfortable, and the limited field of view requires the development of different scanning strategies. Furthermore, due to the limited data–link between the remote site and the operator, transmission delays, and the use of enlarged geometric fields of view (zoomed–in cameras), loss of visual stability occurs during camera rotations which may impede adequate mapping of spatial information (the viewing direction of the operator and that of the camera may differ: objects are not located where they are depicted). These drawbacks may counteract the positive effects of head slaved camera control.

Experimental results show that head slaved camera control increases search speed but also enlarges the search path as compared to manual (joystick) control. Furthermore, the results also confirm the increased susceptibility to mismatches between visual information and proprioceptive information due to time delays or zooming (Van Erp & Van den Dobbelsteen, 1998a, 1998b).

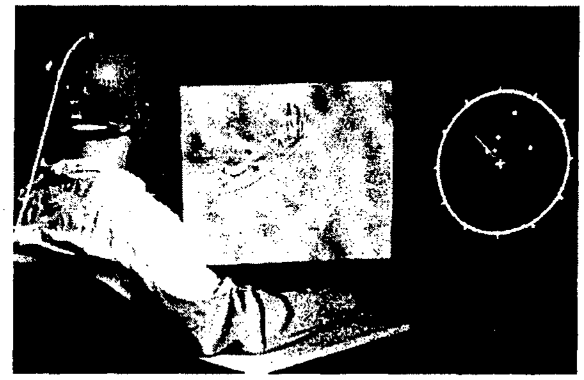

Figure 14. Experimental setting in which the operator controls the simulated camera by means of a head–coupled sensor.

4.7 Concluding remarks

The results of the examples show that innovative interface design can significantly improve operator performance without removing the human operator from the control loop or enlarging the data–link requirements. It should be noted that these experiments should be viewed as examples of the contribution of human factors to the design of interfaces. They only showed a limited set of possibilities to enhance operator performance. For instance, other types of displays (e.g., tactile or 3D auditory displays) or emphasis on operator training methods may also be employed in order to support the operator in (multiple) UAV control methods.

5 Conclusions

The paper described two human factors approaches to reduce the field of tension between operator performance and data–link capacity. The first approach is based upon developing the most economical man–machine interface by presenting task–critical information only, and omit information that is of less or no use to the operator. The idea is that omitting this information reduces the data–link requirements, without hampering operator performance. This approach was illustrated with the example of the viewing system for driving an Unmanned Ground Vehicle. The second approach was based upon developing advanced interface designs. This approach is focussed on providing the operator with task critical cues (e.g. high quality visual motion cues for tracking tasks) that may not be inherently present in the tele-operating environment. Point of departure for this approach is that it does not increase the data-link requirements. Therefore, it employs new control devices (e.g. head-coupled control), and intelligence present in the control station (e.g. prediction techniques). Research has shown that both approaches can succeed in reducing the data-link and/or improving operator performance.

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An Evaluation of Input Devices and Menu Systems for Remote Workstations

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SUMMARY

It is likely that the future air fleet will include uninhabited air vehicles (UAVs) that can be controlled by an operator in a remote location. Such a system will require the operator to experience the same view as the onboard camera to maintain control and keep track of the uninhabited vehicle. It should be borne in mind that uninhabited vehicles are not likely to be continuously operational but deployed only when necessary. The interface must therefore be intuitive, as long periods of time could elapse between missions. The training needs of the operator should therefore be less intensive than those currently necessary for the manned aircraft fleet. As missions may employ a semi-autonomous mode of operation, there is a requirement for transparency between the system and the operator inputs. This paper reports an investigation of the utility of three Windows-driven menu systems and four input devices. Performance with a touchscreen, touchpad, keyboard and mouse was compared on a waypoint re-routing task. It was anticipated that the innovative touchscreen would enhance performance when compared to the more conventional input methods of keyboard or mouse. The literature suggested that performance with the touchpad would not be optimal. The experiment was run in three phases, each phase using a different menu structure. Pull-down menus, pop-up menus and horizontal menus were included. The results show that in this type of scenario, less emphasis should be placed on the menu system to be used than the input device, although pop-up menus may be less desirable. The mouse and the touchscreen provide performance advantages in comparison to the keyboard and the touchpad.

1. INTRODUCTION

It is likely that the future air fleet will include uninhabited vehicles that can be controlled by an operator in a remote location. Such a system will require the operator to experience the same view as the onboard camera to maintain control and keep track of the vehicle. It should be borne in mind that uninhabited vehicles are not likely to be continuously operational but deployed only when necessary. The interface must therefore be intuitive as long periods of time could elapse between missions. The training needs of the operator should therefore be less intensive than those currently necessary for the manned aircraft fleet. As missions may employ a semi-autonomous mode of operation, there is a requirement for transparency between the system and the operator inputs. This places the emphasis for control on the design of an intuitively usable workstation. Generally there are three ways to input information: cursor commands (mouse or touchpad), point commands (light pen or finger) and direct command methods that use keyboard input or voice input for sequence control (Gibbons, 1992). This paper will investigate the utility of three Windows-driven menu systems and four input devices to aid control of a remote vehicle. Performance with pull-down, pop-up and horizontal menu systems, and keyboard, mouse, touchpad and touchscreen input devices, will be considered.

1.1 Menus

Menus are an effective method of interface design and can make interface operation easier for users. They offer choices that have only to be recognised by the user, rather than requiring the user to learn and recall complex syntax and command strings, thus using less cognitive resources and facilitating concentration on the primary task (Schneiderman, 1998). Menu systems can therefore be particularly useful when intermittent use of a system is likely; this lends itself to the control of UAVs. In addition, they enable the user to see the range of alternatives available (Newman and Sproull, 1984). Menus also lead to fewer errors than command-based interfaces, because they allow only certain actions to be performed (Benbasat and Todd, 1993). Once a user has indicated his menu choice via the input device he will receive feedback indicating what has happened, making a menu interface appealing to users as well as easy to use. However, menu systems reduce user freedom as choices are dictated by the system (Booth, 1992). There are many different types of menu, but the ideal menu for use within a particular interface emerges only as a result of careful interface design.

Pull-down menus have top-level headings permanently displayed on the menu bar at the top of the screen/window. The user displays the menu by "pulling down" or selecting an item (BS ISO, 1997). Further

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

selections can then be made from the displayed menu. Although the top level choices are always displayed, the menus can obscure screen space when they drop down.

Pop-up menus do not have a permanent menu bar displayed. A click on the input device "pops up" the menu wherever the cursor happens to be at the time (BS ISO, 1997). The advantages are fewer cursor (and therefore hand) movements as the user does not have to keep moving the cursor to the top/bottom of the screen to make a selection (Newman and Sproull, 1984). In addition, this format saves screen space. However, as the menu (and associated sub-menus) may appear in different places there is no chance for the user to learn the spatial location of frequently used menu items. When information is in a constant location, users acquire expectations about where items will appear, and this gradually improves response times (Norman, 1991).

Horizontal menus are the older type of menu commonly found on DOS-based systems. One top-level menu item and its associated sub-choices are displayed on a status bar usually at the bottom of the display. To change the menu the user selects the top level to the left of the display bar and all the viewable options change. However, only one mode can be presented at any time, requiring the operator to toggle between top-level menus as appropriate. One further limitation exists: there will be a limit to the number of menu items that can be displayed (Newman and Sproull, 1984). However, the advantage is that these menus do not obscure the screen.

1.2 Input Devices

It has been argued that input devices such as touchscreens, mice, joysticks and trackballs have an advantage over the keyboard because they allow manipulation of the screen content in a direct manner (Han, Jorna, Miller and Tan, 1990). However, Gould, Green, Boies, Meluson and Rasamny (1990) found that data entry could be faster with the keyboard than other devices if aided automatic string completion was used on a task. Hence, it appears that the nature and conditions of the task can determine the most desirable device. For example, a mobile ground-station for a UAV may have different requirements from a fixed-base command and control station headquarters. The keyboard is, however, often regarded as the most suitable device for data entry (Gould et al, 1990).

The mouse is considered to be quick and accurate, especially on smaller targets (Sears and Schneiderman, 1991). However, it does have some disadvantages. First, it consumes desk space, as does its lead, which can be distracting or become entangled (Brown, 1988). Secondly, it needs some practice to acquire the skill. For very long motions it also requires the whole device to be picked up and repositioned. Finally, it is a moving part, which makes it liable to "getting lost" in public applications, and it is not as rugged as a touchscreen for this type of application (Schneiderman, 1998). Brown (1988) suggests that in mobile environments a mouse may not be the most suitable input device. Once again in a mobile UAV unit, these may be important considerations. However, there are some advantages in the use of a mouse. During operation the hand does not obscure the screen, it is comfortable to use and may be the preferred input device for click and drag manoeuvres. It is now the industry standard and most potential users would already be familiar with it.

In a review, Schneiderman (1998) concludes that the major advantage of the touch tablet is that the hand does not obscure the screen as it would in touchscreen use and that it may be more comfortable for the user. However, it does take up desk space. In addition Han et al (1990) found that performance is very slow with the tablet and users do not like it.

Touchscreens are considered to be a natural pointing device (Sears, 1991). They are reported to be simple to operate and easy to learn, with rapid performance and potentially low error rates (Sears and Schneiderman, 1991). It has been reported that the early problems with precision have now been resolved by advances in technology (Schneiderman, 1998). However, touchscreens are not ideal for typing large amounts of data. In his review, Schneiderman (1998) points out that touchscreens are very durable as they have no moving parts, making them ideal for military use. Gould et al (1990) state that touchscreens have "behavioural advantages". Less space is required for their use and they are also a very flexible interface, capable of presenting various displays to suit the task, such as icons, windows and keyboards. A potential problem with touchscreens, however, is the possibility of touch biases. Touch biases refer to differences between the intended and actual locations selected. This could also account for some of the reduced accuracy sometimes seen with a touchscreen.

Karat et al (1986) state that improved performance seen on touchscreens may be due to the fact that mouse and keyboard operation involves more cognitive processing, whereas pointing is a highly automated skill for humans. Schneiderman (1998) points out that mouse use requires not only more cognitive processing, but also hand-eye co-ordination when moving the cursor. Sears and Schneiderman (1991) therefore conclude that the touchscreen is as fast, or faster than, the mouse except for very small targets. Sears (1991) also suggests that the touchscreen allows "more natural selections" (pp 265). This could be relevant for UAVs, as the operator may be under high workload, and the lower the cognitive processing required the better.

In general the most appropriate input device seems to depend on the type and demands of the task, the operational environment and the end-users (Schneiderman, 1998; Fernandez et al, 1988; Sears, 1991). However, it was anticipated that an innovative touchscreen device would enhance performance on a waypoint re-routing task when compared to the more conventional input methods of keyboard or mouse.

2. METHOD

2.1 Participants

Thirty-six participants (26 male, 10 female) were selected from an opportunity sample of Defence Evaluation and Research Agency (DERA) staff. They were aged 20 to 34 with a mean age of 25. They reported normal or corrected-to-normal visual acuity. Of the 36 participants, 4 were left-handed and 32 right-handed.

2.2 Materials

A demonstration trial, a practice trial and two main trials were generated using a Silicon Graphics Onyx[2] computer, presented on a monitor with a 47.5 cm x 30 cm visual screen. Each trial consisted of a static map display with a pre-determined set of waypoints that indicated the planned route a UAV was to follow. The demonstration trial and the practice trial consisted of five tasks: pre-flight re-routing; launch of vehicle; in-flight re-routing due to a surface-to-air-missile (SAM) zone; acknowledgement and identification of a target; and, finally, recovery of the vehicle. For each of the main trials there were eight tasks, the five tasks as before and an additional pre-flight re-route, in-flight re-route and target acknowledgement and identification.

The task required participants to carry out actions based on events as they occurred. The events were signified by audio messages, generated by a Silicon Graphics Sound Editor software package. New waypoints, targets and launch and recovery points were also indicated by flashing letters or symbols (as appropriate) on the screen.

Participants were asked to carry out actions using one of four input devices. The touch tablet used was a Cirque "Smart Cat" touchpad and will therefore be referred to as the touchpad within this paper. Three different menu types were used to allow the participants to interact with the display.

2.3 Design

A two-way mixed measures design was used. The independent measures were input device (four levels) and menu type (three variables). Each participant was presented with each of the input devices: keyboard, mouse, touchpad and touchscreen. However, participants were exposed to only one of the menu types: pull-down, pop-up or horizontal.

The dependent measures were error rate (calculated as the number of times a task was not correctly completed), response time (the time taken for participants to press a response key) and total task time (calculated as the overall time taken to complete a trial). For the purposes of reporting the data the main trials were broken down into five tasks. Replicated tasks were simply meaned. Subjective measures were also recorded in pre- and post-experimental questionnaires.

Each participant was presented with only one of the main trials (1 or 2) for each input device. Main trial 2 represented a reversal of events and a 180^0 rotation of main trial 1. To reduce familiarity with the route, for all participants the first input device presented was shown with main trial 1, the second with main trial 2, the third with main trial 1 and the fourth with main trial 2.

2.4 Procedure

To prevent learning and/or order effects, the order of use of input devices was balanced using a replicated 4 x 4 design. Twelve participants completed each menu system. Upon arrival participants were presented with written instructions for completion of the task. They were asked to complete a demographic questionnaire that included questions regarding their familiarity with and preference for the four input devices and their familiarity with the appropriate menu system. They were then asked to sign consent forms. A practical demonstration was given by the experimenter, on how to complete the task, with emphasis on the menu system to be used. Following this, participants received a further set of instructions outlining the first input device to be used. Participants then completed one practice trial and one main trial. Before each of the subsequent input devices was used, device-specific instructions were presented, but no further demonstrations were given.

During the practice trials, data were not recorded. In the main trials, response times were recorded in seconds to four decimal places. Following completion of the experiment, participants completed a post-experimental questionnaire that asked them to rank again their preferences for the input devices. Participants were then debriefed.

3. RESULTS

3.1 Objective Measures

As explained in the design section of the method, each participant was presented with one of the two main trials for each input device. There is evidence of training between the two trial runs, whereby run 1 produced significantly longer response times than run 2. However, this does not interact overall with the menu systems and input devices and will therefore not be reported further.

3.1.1 Error Rates

Very few errors were made in the trials (0.4%). An error analysis was therefore not conducted.

3.1.2 Response Times (RTs)

All data required a log transform. Missing values were estimated. Differences between input devices and menu systems were analysed using the Newman-Keuls range test. Outliers were removed before analysis (0.6%). All means presented are back-transformed. Trials in which participants had responded incorrectly were not included in the analyses. A two-way mixed Analysis of Variance (ANOVA) was performed on the factors Menu and Input Device.

3.1.2.1 Pre-flight re-routing

A significant main effect of Input Device ($F(3, 99) = 45.62$, $p<0.001$) was found. Post hoc analyses for the main effect of Input Device showed that the mouse and touchscreen produced significantly faster response times than the touchpad ($p<0.001$) and the keyboard ($p<0.001$). Mean RT scores for Input Device and Menu are shown in Table 1.

Input Device	Pull-down	Pop-up	Horizontal	Mean
Keyboard	21.31	21.12	18.07	**20.17**
Mouse	12.59	14.84	13.40	**13.61**
Touchpad	20.22	22.61	20.34	**21.05**
Touchscreen	13.43	12.40	13.32	**13.05**
Mean	**16.89**	**17.74**	**16.28**	

Table 1: Mean RT for Input Device and Menu for Pre-flight Re-routing (in seconds)

3.1.2.2 Launch of the vehicle

Significant main effects of Menu ($F(2, 125) = 17.81$, $p<0.001$) and Input Device ($F(3, 125) = 6.26$, $p<0.01$) were found. Post hoc analyses for the main effect of Menu showed that the horizontal and pull-down menus produced significantly faster response times than the pop-up menu ($p<0.01$). Post hoc analyses for the main effect of Input Device showed that the touchscreen and mouse produced significantly faster response times than the keyboard ($p<0.001$) and the touchpad ($p<0.001$). Mean RT scores for Input Device and Menu are shown in Table 2.

Input Device	Pull-down	Pop-up	Horizontal	Mean
Keyboard	5.10	5.99	4.31	**5.14**
Mouse	3.26	4.49	3.88	**3.88**
Touchpad	4.76	6.19	4.96	**5.30**
Touchscreen	3.68	3.94	3.84	**3.82**
Mean	**4.20**	**5.15**	**4.25**	

Table 2: Mean RT for Input Device and Menu for the Launch of the Vehicle (in seconds)

3.1.2.3 In-flight re-routing

Significant main effects of Menu ($F(2, 33) = 3.65$, $p<0.05$) and Input Device ($F(3, 99) = 34.63$, $p<0.001$) were found. Post hoc analyses for the main effect of Menu showed that the pull-down menu produced significantly faster response times than the pop-up ($p<0.05$) and horizontal menus ($p<0.05$). Post hoc analyses for the main effect of Input Device showed that the touchscreen and mouse produced significantly faster response times than the keyboard ($p<0.001$) and the touchpad ($p<0.001$). Mean RT scores for Input Device and Menu are shown in Table 3.

Input Device	Pull-down	Pop-up	Horizontal	Mean
Keyboard	17.04	17.41	17.33	**17.26**
Mouse	10.86	13.35	13.51	**12.57**
Touchpad	16.91	18.28	20.00	**18.40**
Touchscreen	11.37	14.12	14.67	**13.39**
Mean	**14.05**	**15.79**	**16.38**	

Table 3: Mean RT for Input Device and Menu for In-flight Re-routing (in seconds)

3.1.2.4 Acknowledgement and identification of a target

Significant main effects of Menu ($F(2, 33) = 5.98$, $p<0.01$) and Input Device ($F(3, 99) = 54.60$, $p<0.001$) were found. There was also a significant interaction between Input Device and Menu ($F(6, 99) = 2.85$, $p<0.05$). Post hoc analyses for the main effect of Menu showed that the pull-down and horizontal menus produced significantly faster response times than the pop-up menu ($p<0.01$). Post hoc analyses for the main effect of Input Device showed that the touchpad ($p<0.01$), touchscreen ($p<0.001$) and the mouse ($p<0.001$) produced significantly faster response times than the keyboard. The touchscreen and the mouse also produced significantly faster response times than the touchpad ($p<0.001$). In addition, the mouse produced significantly faster response times than the touchscreen ($p<0.01$).

Post hoc analyses for the interaction between Input Device and Menu showed that for the pull-down menu the touchpad ($p<0.05$), the touchscreen ($p<0.001$) and the mouse ($p<0.001$) produced significantly faster responses than the keyboard. The touchscreen and the mouse also produced significantly faster response times than the touchpad ($p<0.001$). For the pop-up menu the touchscreen and the mouse produced significantly faster response times than the keyboard ($p<0.001$) and the touchpad ($p<0.001$). For the horizontal menu the touchscreen ($p<0.05$) and the mouse ($p<0.001$) produced significantly faster response times than the keyboard. The mouse also produced significantly faster response times than the touchpad and the touchscreen ($p<0.001$). For the keyboard the horizontal menu produced significantly faster response times than the pop-up menu ($p<0.05$). For the mouse and touchpad the pull-down and horizontal menus produced significantly faster response times than the pop-up menu ($p<0.01$). Mean RT scores for Input Device and Menu are shown in Figure 1.

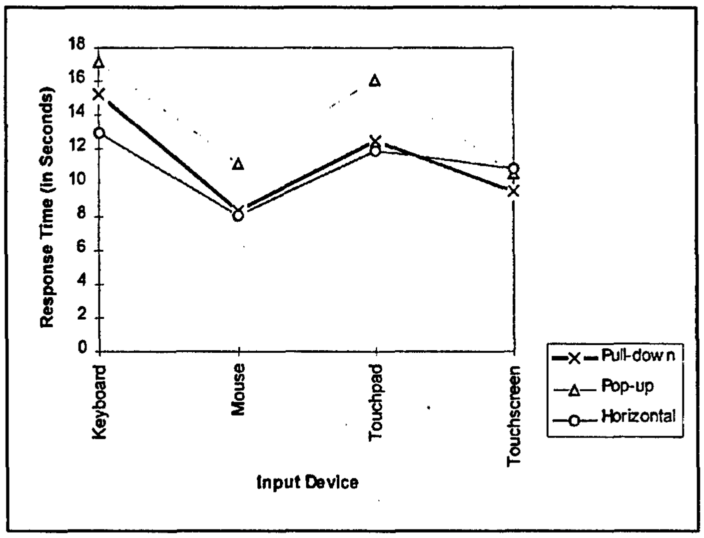

Figure 1: Graph showing RTs for Input Device and Menu for the Acknowledgement and Identification of a Target (in seconds)

3.1.2.5 Recovery of the vehicle

Significant main effects of Menu ($F\ (2, 33) = 3.80$, $p<0.05$) and Input Device ($F\ (3, 99) = 7.48$, $p<0.001$) were found. Post hoc analyses did not show the source of the significant main effect of Menu. However, it can be seen in Table 4 that there was a trend for the pull-down and horizontal menus to produce faster response times than the pop-up menu. Post hoc analyses for the main effect of Input Device showed that the touchscreen ($p<0.05$) and the mouse ($p<0.001$) produced significantly faster response times than the touchpad. The mouse also produced significantly faster response times than the keyboard ($p<0.001$). Mean RT scores for Input Device and Menu are shown in Table 4.

Input Device	Pull-down	Pop-up	Horizontal	Mean
Keyboard	3.32	7.64	2.91	**4.62**
Mouse	2.38	4.79	2.64	**3.27**
Touchpad	4.11	7.69	4.28	**5.36**
Touchscreen	3.44	4.38	3.71	**3.85**
Mean	**3.31**	**6.12**	**3.39**	

Table 4: Mean RT for Input Device and Menu for Recovery of the Vehicle (in seconds)

3.1.2.6 Total task time

A significant main effect of Input Device ($F\ (3, 129) = 43.84$, $p<0.001$) was found. Post hoc analyses showed that the touchscreen and the mouse produced significantly faster response times than the keyboard ($p<0.001$) and the touchpad ($p<0.001$). Figure 2 illustrates the total task time.

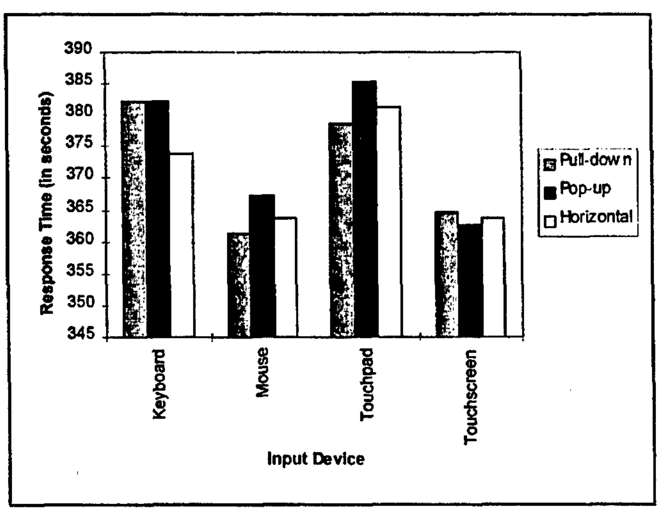

Figure 2: Mean RT for Input Device and Menu for Total Task Time (in seconds)

3.2 Subjective Measures

3.2.1 Pre-experimental familiarity with input devices

Participants were asked to rate how familiar they were with each of the four input devices to be used, before participating in the trial. It can be seen in Table 5 that the participants were more familiar with the use of the keyboard and the mouse than the touchpad and the touchscreen. Mean ratings for familiarity with the input devices are shown in Table 5.

Input Device	Never Used	Unfamiliar	Familiar	Often Used
Keyboard	0	0	2	34
Mouse	0	0	2	34
Touchpad	8	12	15	1
Touchscreen	4	12	19	1

Table 5: Familiarity with the Input Devices: Pre-experimental Mean Ratings

3.2.2 Pre-experimental preferences for input devices

Participants were also asked to rank order their preferences for the four input devices before participating in the trial. It can be seen in Table 6 that the participants ranked the keyboard and mouse highly, in line with their familiarity of use. The mouse was the preferred input device. The ranks shown represent 35 of the 36 participants' data. One participant's data were removed as the post-experimental questionnaire was incorrectly completed. Hence it could not be used for comparison. Mean ranks for the input devices are shown in Table 6.

Input Device	1st	2nd	3rd	4th
Keyboard	11	12	10	2
Mouse	16	16	3	0
Touchpad	1	2	3	29
Touchscreen	7	5	19	4

Table 6: Pre-experimental Mean Ranks for the Input Devices

3.2.3 Pre-experimental familiarity for menu systems

Participants were also asked about their familiarity with the type of menu system they were about to use in the trial. As only one third of participants were presented with each menu type, there were only 12 participants in each group. It can be seen in Table 7 that participants were more familiar with the pull-down menu and least familiar with horizontal menu systems. Mean ratings for familiarity with the input devices are shown in Table 7.

Menu Type	Never Used	Unfamiliar	Familiar	Often Used
Pull-down	0	0	0	12
Pop-up	0	1	1	10
Horizontal	0	2	3	7

Table 7: Familiarity with the Input Devices: Pre-experimental Mean Ratings

3.2.4 Post-experimental preferences for input devices

Participants were asked again to rank order their preferences for the four input devices on completion of the trial. It can be seen in Table 8 that the participants ranked the touchscreen as the preferred device. It is interesting to note that the keyboard was ranked third overall. The ranks shown represent 35 of the 36 participants' data as one participant gave equal ranks to devices, despite the instructions given for completion. This participant's data were therefore removed. Mean ranks for the input devices are shown in Table 8.

Input Device	1st	2nd	3rd	4th
Keyboard	0	3	18	14
Mouse	8	24	3	0
Touchpad	3	2	12	18
Touchscreen	24	6	2	3

Table 8: Post-experimental Mean Ranks for the Input Devices

4. DISCUSSION

For total task time, pre-flight re-routing, launch of the vehicle, in-flight re-routing and recovery of the vehicle, the results show that the mouse and the touchscreen produced performance advantages in comparison to the keyboard and the touchpad, on a waypoint re-routing task. However, for target acknowledgement and identification, the mouse gave faster response times than the touchscreen. The touchscreen may not have provided performance advantages over the mouse because it did not prove to be 100% reliable over the trial. There were some instances when the touchscreen did not respond at the initial press. However, this was not reported as a problem most of the time and may sometimes have been due to user style. For the acknowledgement and identification of a target, the touchpad provided performance benefits in comparison to the keyboard. For the recovery of the vehicle, the mouse also gave performance advantages over the keyboard.

In designing the experiment it was difficult to decide how similar to keep the use of each menu and input device. The aim was to allow the advantages of each menu and input device to be maintained within a similar design structure to enable fair comparisons to be made. However, with the keyboard this was particularly difficult as the task involved direct manipulation. This type of task is inherently unsuited to the use of a keyboard. To permit the input of waypoint data when using the keyboard, it was necessary to use the tab keys for some of the menu selections, but the cursor keys for others. Participants were also required to press the space bar rather than the return key to select menu options and acknowledge dialogue boxes. In addition, keyboard inputs for the pull-down and pop-up menus required other buttons to be pressed to display menu options. For example, with the pop-up menu, the control button had to be pressed. This may have contributed to the performance advantage shown by the horizontal menu in comparison to the pop-up menu, when using the keyboard. It is more difficult to remember a particular key than simply to make a selection with a mouse. More familiarity may be required with the keyboard to increase the speed of use. Effective use of short-cut keys would help, but these could be forgotten due to intermittent use.

It is likely that the poor performance of the touchpad could be attributed partly to the speed/distance ratio of the scrolling mechanism when movements of large distances were required. Several repetitive movements were required to scroll across the screen from one side to the other. A further problem participants experienced with the touchpad was deselecting items by accidentally tapping the pad when moving the cursor to a menu option. Another possible explanation is the unfamiliarity of the participants with this device. However, this could not be the only explanation, as participants were also unfamiliar with the use of touchscreens.

It is interesting to note that the results do not show a significant performance benefit overall (total task time) for any of the three menu systems used. However, for the launch of the vehicle and the acknowledgement and identification of a target, the results show that the pull-down and horizontal menus produced faster response times than the pop-up menu. It is not surprising that the pop-up menu required extra time to respond, as an additional button press is required to enable the top-level menus to be observed before a selection can take place. Some participants also found that it was inconvenient to have the display "pop-up" near the cursor, blocking part of the display. In addition, further action would need to have been taken to move the position of the menu on the screen to a more suitable location. For in-flight re-routing, however, the results showed that the pull-down menu gave faster response times than both the pop-up and horizontal menus.

The interaction between Input Device and Menu for acknowledgement and identification of a target showed that, for the pull-down and pop-up menus, the touchscreen and mouse gave similar performance advantages. For the horizontal menu the mouse performed the fastest. One possible explanation is that a smaller movement was needed with the mouse to identify the target than for the touchscreen, as the finger was usually removed from the screen between selections. As the buttons in this horizontal menu were adjacent, more effort would be required in using the touchscreen than the mouse. It is interesting to note that, for the keyboard, the horizontal menu provided performance advantages over the pop-up menu. However, for the mouse and touchpad the horizontal and pull-down menus gave similar performance levels above those for the pop-up menu. It should be noted that mode errors occurred more frequently with the horizontal menu. Such errors typically occurred between the pre-flight and the in-flight re-routing on the second re-route task. Once the target had been identified a change of mode switched to mission planning. As the dialogue boxes to enter the waypoint information were similar to those in the in-flight mode some participants did not realise that they were not in navigation mode. It appears that performance with the touchscreen is affected less by menu type than the remaining input devices (refer to Figure 2).

The subjective data show that one third of the participants were unfamiliar with the use of a touchscreen and a touchpad, whilst some participants had never used such devices before. The majority of participants were familiar with the menu system to which they were exposed, but they were less familiar with the horizontal menus than the pull-down and pop-up menus. This is not unexpected given the use in industry of Microsoft Windows-based products. It would have been interesting to ask the participants for a subjective preference for menu type. However, this was not possible as participants were exposed to only one menu system and did not know about the testing of others until they had completed the experiment.

A comparison of the pre-experimental and post-experimental rank orders for participants' preferences for the input devices showed an interesting difference. Before the trial began, participants ranked the mouse as the preferred input device and the keyboard second. However, on completion of the experiment, the touchscreen was ranked as the preferred input device and the mouse second. It is possible that the difference in pre- and post-experimental rankings could be partly due to the specific scenario being used to rank the devices post-experimentally. Nevertheless, it is useful to note that the majority of the participants preferred the touchscreen rather than the mouse for this task, and that the keyboard was not placed high in the ranks.

Comments made during the trials by the participants were recorded for later discussion. One comment referred to the speed at which the trial was run, explaining that it was easy to get distracted because the trial was too slow. However, the task had to be run at a slower pace than envisaged to ensure the feasibility of participants being able to complete the first trial when the task, input devices and menu system would be unfamiliar to them. In a real-world scenario, a similar task would require a monitoring capability, so the distraction element may have actually made the task more realistic. It was also suggested that the mouse cursor should be enlarged and that an accelerated mouse may be more appropriate for the task. Other input devices, such as a trackball, or the use of direct voice input, could have been considered. A further suggestion was that some buttons could be permanently available on the screen for touchscreen use; this would reduce the number of menu options required on the display. It was recognised by some participants that actions were required only when a new waypoint marker had been reached. Unfortunately this was a consequence of the way the program was written; event markers were required to prompt activity.

In conclusion, this research has illustrated the significance that an input device can have for operator performance on a waypoint re-routing task. It appears that in this type of scenario less emphasis should be placed on the menu system to be utilised, although pop-up menus may be less desirable. The focus should therefore be placed on the device for interaction. Future workstation design should therefore consider the use of a touchscreen or mouse for control of remotely-operated vehicles. A touchscreen may be preferable as its performance seems more stable across menu systems and was reported as the preferred choice by operators in this experiment. Future research will investigate the utility of the mouse and the touchscreen further.

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This work was funded by Technology Group 5 (Human Sciences and Synthetic Environments) of the UK Ministry of Defence's Corporate Research Programme.

Advances in UAV Data Links: Analysis of Requirement evolution and implications on future equipment

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1. ABSTRACT

This paper resumes the fundamental operational requirements that a UAV must accomplish to be effectively performant in a military and civil environment. Moving from these considerations, a list of technical requirements for Data Link systems to be employed is derived and a suitable Data Link architecture, based on the evolution of current Marconi's J-Band Data Link for CATRIN-SORAO programme is presented.

2. INTRODUCTION

UAVs (Unmanned Air Vehicles) are getting higher and higher importance in the last years' battlefield scenarios and, in general, in a variety of military operations such as ground surveillance, peace keeping and battle damage assessment. The experiences gained by U.S. Army Forces during the Gulf War and by NATO Forces in recent Bosnia operations have demonstrated that UAVs can play a crucial role everytime a complete situation awareness of a hostile or sub-hostile territory is needed. Moreover, use of UAVs for civil applications is still at an early stage, but is growing rapidly in some countries such as Japan. However, wide employment of these aircrafts calls for a series of improvements in performance and reliability and requires a growing level of integration with both military and civil air traffic control systems. This paper will address all these issues and their consequences on new Data Links architectures.

3. SCOPE OF THE PAPER

Scope of this paper is to analyse typical UAVs requirements to be fulfilled, to present some considerations on technical characteristics of all communication systems involved and to derive, on the basis of Marconi Communications experience, a possible architecture for newly designed Data Links.
This work will be outlined as follows:

- Section 4 presents some emerging UAV operational requirements introduced by new scenarios and possible applications.
- Section 5 relates on technical UAV Data Link requirements and presents some related design considerations. The matter is subdivided in two parts: the first one (Sec. 5.1) briefly lists those requirements that can be considered as "consolidated" and virtually constitute the basis of every UAV system; the second one (Sec.5.2) relates to issues to be considered to accomplish new operational requirements.
- Section 6 presents a possible architecture based on preceding considerations.

4. UAV OPERATIONAL REQUIREMENTS

With respect to the past, some present requirements have to be extended or modified while some new ones have arisen. In the following this requirement evolution will be examined in greater detail.

4.1 More extended and complex military scenarios

Usage of Tactical UAVs is more and more frequent in such operations as peace keeping or ground surveillance over crisis zones; in many cases, military Forces taking part of missions act as a "third party" not directly involved in local warfare situations. This often implies the ability for a Tactical UAV to operate over wider areas than in the past, while maintaining its ground-based control centre outside the boundaries of the country to survey. Moreover, rapid deployment of ground equipments near the operation territory could be extremely risky in presence of guerrilla-organised troops or could be difficult due to lack of logistic facilities (roads, airports, etc.). All these issues have increased the operational range requirements: at the present a limit of 200 Km can be considered as necessary for Tactical UAVs; for Medium Altitude Endurance UAVs (MAE UAVs) this limit must be raised up to 1000 Km.

4.2 Multi-sensors capability

For a UAV to be capable to operate effectively in most meteorological and operational conditions, use of different types of sensors is requested: for instance, IR sensors can be useful for night surveillance at short-medium distance from the targets, but a SAR sensor would allow better targets resolution at relatively higher ranges. For all these reasons, UAVs should be capable to host different sensors (possibly more than one at the same time) and a Data Link system able to collect their data and transmit them to the Ground Control Station.

4.3 Data dissemination and communication issues

Rapid deployment of a communication network for data exchange between Tactical Command & Control centre and some Ground Units spreaded over the territory can be difficult, especially in presence of natural obstacles (mountains and valleys) that can limit the functionality of terrestrial communication devices such as VHF radio equipments or line-of-sight (LOS) data links. In these cases, the UAV Data Link system can be equipped with an additional broadcasting function in order to directly disseminate sensors and tactical data over a wide area or connect locally a small number of Ground Units: this can represent a valid alternative to satellite communication equipments, that often suffer from lack of available channels and usually offer less channel bandwidth. Moreover, satellite

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

links are generally characterised by lower ECM resistance, higher interceptability and higher latency with respect to wide band Data Links for UAV.

4.4 Operations over civil areas

Another practical effect of considerations presented in Sec. 4.1 is the need to fly over both military and civil areas of one or more countries (possibly not involved in the operations), thus potentially interfering in commercial airways and introducing a wide series of problems concerning flight safety. This calls for a growing level of integration with present Air Traffic Control (ATC) and future Air Traffic Management (ATM) to ensure that the UAV can be properly monitored (even if not directly controlled) during non operational phases of flight and during possible manoeuvres (including takeoff and landing) in proximity of airports open to civil traffic. A further improvement of overall reliability of UAVs and, in particular, their communication systems is also required.

4.5 Non-military applications

Ground surveillance through a UAV can also have importance in a wide series of non-military applications: for example, during search and rescue operations over sea and land (in case of natural calamity such as earthquakes, floodings, etc.) whenever meteorological conditions or other factors can determine too risky conditions for a manned aircraft. Other possible applications can be coastal surveillance (for illegal immigration and smuggling control purposes), police operations and agricultural aid (for fertilizer distribution, etc.). With respect to military applications, a civil UAV presents less security constraints (e.g. ECCM capability, etc.) but requires all the features indicated in Section 4.4 to fly over civil areas.

4.6 UAV for non-lethal weapons deployment

Non-lethal weapons (including foams, nets, irritants, obscurants, acoustic devices, optical munitions, etc.) are those weapons designed to degrade the capabilities of material or personnel and yet avoid unintentional human casualties. Use of non-lethal weapons for police, peace-keeping and military application is becoming wider and wider and UAV appear to be an ideal platform for non-lethal weapons deployment in many scenarios. From a data link point of view, this application involves again the issues described in Sec. 4.2 and Sec. 4.4 (i.e. multi-sensor capability and operations over civil areas), but further additional requirements arise, associated to the authorisation to release the non-lethal weapons: for safety and legal reasons high availability / reliability and very low bit error rate are required for the data link to transmit these commands.

4.7 Uninhabited Combat Air Vehicles

At present Uninhabited Combat Air Vehicles (UCAVs) are one of the applications more debated by the UAV Community: if feasible, a UAV, capable to substitute manned fighters in the missions with the highest risk for the crew (such as low quote ground attack and/or Suppression of Enemy Air Defenses (SEAD)), would find a very high interest by the Military Forces. UCAVs however are expected to enter in service at long term (after 2010) as their design presents technical issues considered very critical, concerning mainly two areas: the demanding artificial intelligence required, related to UCAV autonomous situation awareness and decision planning, and the complex communication system, that, according to research / pre-feasibility activities being performed in the world (including the NIAG SG 53 Study "UAV Interoperability"), appears to be well above the technical characteristics of present state-of-the-art UAV data link systems. From a communication perspective, main issues concerning UCAVs are:

- **UCAV control/monitoring in combined missions**: UCAVs are envisaged to perform their missions in complex scenarios where several types of aircraft and also Ground and Naval Forces may be present; UCAVs and manned aircraft may be involved in combined attacks. Two main functions are required to the UCAV data link system: the first is to allow UCAV control / monitoring in all the mission phases by different platform (airborne, shipborne or land-based) one at a time; the second is to ensure the UCAV integration in the air situation awareness network, exploiting UCAV data according to criteria used for other aircraft. The communication systems architecture needs to fulfil these two functions, which impose different and sometimes opposite requirements.
- **Link integrity / ECM robustness**: in a UCAV all main functions (including weapons control) depend on data link system control/monitoring. Moreover, ECM environment is envisaged to be very severe, as UCAVs are planned to be used also in SEAD missions. Link integrity and ECM robustness requirements appear therefore very demanding.
- **Link availability / reliability**: UCAV operations need an overall data link availability (including atmospheric fading, multi-path losses, antennas misalignment, etc.) higher than 99%, well above the 90-95 % typically required to UAV payload wideband data link. High overall reliability is also required for the data link system, recommending either equipment redundancy or re-configuration capability.
- **Beyond line-of-sight UCAV control**: typical UCAV missions (ground attack, SEAD, etc.) involve low quote operation at range of hundreds of Km; the data link system is required to ensure high band and low latency connections to allow continous and reliable UCAV control also in these conditions.

4.8 Interoperability

Interoperability becomes highly desirable when UAV has to be used in a multi-national environment or, in general, when multiple UAV systems must coexist in the same scenario.

A NIAG group (NIAG SG53) has been established in 1997 to define design recommendations and is now at the end of its effort. Five nested levels of interoperability have been defined, starting from standardisation of interfaces/protocol of Ground Stations to guarantee flexible interconnectivity to C^3I networks (Level 1) and arriving to complete UAV and payload control capability by different Ground Stations, including takeoff and landing phases (Level 5).

Interoperability can lead to a variety of advantages (in terms of interfaces, protocol, data format standardisation, etc.) and, consequently, to cost reduction and usage flexibility (due to modules interchangeability). On the other hand, some constraints and drawbacks arise in the short term: for instance, backward compatibility towards existing systems is often required and this implies the design of legacy units to act as interface. Moreover, high level of standardisation can potentially limit the design flexibility or even lead to lower efficiency: for example, usage of standard protocol such as TCP/IP to convey data over Data Link channel can reduce throughput due to the data overhead required; for limited channel bandwidth and high sensor data rate a dedicated protocol can be more suitable. All these matters must be taken into account during Data Link system design.

5. DATA LINK TECHNICAL REQUIREMENTS

5.1 Consolidated requirements

The following requirements are necessary to guarantee a suitable operativity and appear to be almost completely acknowledged by all state-of-the-art systems:

- Operational range: up to 100 NM for Tactical UAVs and up to 500 NM for MAE UAVs
- Availability over 90%
- Low bit error rate on Data Link (between 10^{-3} and 10^{-6} according to data type)
- Low interceptability
- High resistance to ECM
- Low latency for UAV/Payload Command and Control Data
- Limited size, weight and power consumption (SWP)

For instance, Marconi Communications' Data Link for CATRIN accomplishes all requirements for Tactical UAVs: it operates in J band (NATO harmonised band for Mobile Systems) and has a range of up to 100 Km @ 2 Mbit/s (now extendable up to 180 Km through an external Booster Module). It operates on a Time Division Multiplex basis to provide bidirectional communications while accomplishing SWP constraints. It offers high ECCM protection thanks to Frequency Hopping techniques. Further details are listed in [1], while current development activities are described in Sec.6.

5.2 Innovative requirements and design considerations

5.2.1 *EXTENDED RANGE*

New requirements in operational range (i.e. over 200 Km for Tactical UAV) can be fulfilled in different ways: increasing receiver sensitivity, adopting ground and airborne antennas with higher gain and increasing transmitted power.

The first approach appears difficult to be followed: provided that modulation scheme remains fixed, larger bit rates requested by new sensors determine lower sensitivity at the receiver (S/N ratio decreases by 6 dB for a 4 times increment in bandwidth: this means that range reduces by a factor 0.5 for fixed BER, trasmission frequency and modulation scheme). Changing type of modulation (e.g. from MSK to 16-PSK) can reduce the bit rate onto the channel by a factor of 2, but this gain become vanishing if we consider that a 16-PSK receiver is about 4 dB less efficient than MSK type. A good compromise can be reached by selecting suitable data rates depending on sensor type (see Sec. 5.2.3).

The second solution is potentially feasible but implies more directive antennas: these ones require to be installed onto a stabilised platform or, at least, need to be steerable in azimuth and elevation plane to compensate for UAV attitude angles during flight.

Finally, longer ranges can be reached increasing transmission power: nowadays level as high as 20-30 W can be obtained through solid-state devices, offering high reliability and relatively good efficience. Higher power levels (around 100 W) can be reached using vacuum tube amplifiers: they are now available in small housings, suitable to be used even for airborne applications. The actual feasibility depends on SWP constraints, especially those related to the Airborne Data Terminal (ADT).

5.2.2 *BIT ERROR RATE*

Bit error rate (BER) is a primary issue for every Data Link system and in particular for UAV Data Link. Since this is an unmanned vehicle, two levels of channel integrity can be pointed out: from the communication point of view, Data Link must ensure enough low BER to allow effective exploitation of sensors data; on the other hand, it must guarantee high Command&Control reliability during critical phases such as flying over civil areas or during takeoff and landing. For the first issue, due to higher data autocorrelation, especially if related to images, typical acceptable BER is around 10^{-3}-10^{-4}, while in the latter case acceptable values decrease to 10^{-6} - 10^{-9}. All these considerations must be furtherly stressed when related to a UCAV. Since obtaining extremely low physical BER levels on the Data Link channel implies heavy drawbacks on link budget, a better approach consist in reaching a suitable physical channel BER to guarantee sensors data exploitation in most cases, paying attention on BER effects on compressed data (see Sec. 5.2.4) and applying suitable error corrections techniques to selected data (see Sec. 6.1.5) in order to limit their overall error rate to the lowest values indicated above.

5.2.3 *ENHANCED DATA RATE*

The common trend in UAV Data Link performance requirements is oriented towards growing transmission rates: use of SAR (not preprocessed) or high definition EO sensors implies data rates of tenths of Mbit/s; more sophisticated sensors such as LOROP can reach hundreds of Mbit/s. As indicated in Sec. 5.2.1, high bit rate over trasmission channel means large signal bandwidth, thus lower receiver sensitivity and need for higher transmission power. However, this is not the only drawback: for example, if coherent demodulation is adopted to improve modem performance, carrier synchronisation can become a major issue when high trasmission speeds are chosen, leading to modem/synthesiser cost enhancement. Nonetheless, adoption of more complex, constant signal envelope modulation schemes, such as multi-h CPM, implies great trasmitter/receiver complication.

From the above considerations, the following design drivers can be derived: physical channel data rate should be limited at a suitable value, considering the trade-offs between transmitted power, SWP constraints and receiver/modem performances; the gap between physical bit rate and sensor bit rate should then be filled by an efficient data compression technique. A good compromise could be a physical data rate between 2 and 10 Mbit/s associated to a data compression ratio of about 15:1÷20:1 (see Sec. 5.2.4). For particular applications, data rates as high as 45-50 Mbit/s can be considered, provided that the transmitted power is increased to maintain the operational range.

5.2.4 *DATA COMPRESSION*

Data compression becomes mandatory when high definition sensors such as SAR and high resolution EO/IR cameras are mounted on UAVs. In this case, the high bit rate requested (and the related larger bandwidth) could drastically reduce the operational range of Data Link. Compression can help to maintain the physical data rate over the channel at lower levels with respect to uncompressed data transmission.

Efficient compression for EO and IR sensors has already been implemented by Marconi Communications in its Data Link for CATRIN-SORAO programme [1]. Further development activities are in progress to extend compression capability to SAR sensors: a specific study has been performed to recognize the compression technique that best fits the new operational requirements; its results are outlined in the following sections.

5.2.4.1 *Lossless techniques*

Lossless techniques are based on elimination of redundancy associated to the signal: the higher is the redundancy, the more effective is the compression. For instance, let us consider a signal derived from sampling of a video image produced by an EO sensor: adjacent pixels are usually mutually correlated and this feature can be exploited to transmit only essential information (e.g. difference between two pixels). Lossless techniques rely on reversible transforms that permits a complete signal reconstruction at the receiver end; they usually allow low compression rates (typically less than 4:1) and their performance heavily depends on signal type. For all these reasons they do not appear suitable to be implemented in Data Link systems for UAV.

5.2.4.2 *Lossy techniques*

Lossy techniques can reach higher compression rates by associating the concepts listed in the previous paragraph to space-frequency bidimensional transforms and quantisation: only the most significant part of signal informative content is trasmitted over the channel. This inevitably leads to a distorsion of the original signal that cannot be recovered at the receiver end. Apart from subjective figures of merit (such as "compression is effective if the reconstructed image is much similar to the original one"), some objective index of quality can be defined: the most used are the Minimum-Square-Error (MSE) and the Peak Signal-to-Noise Ratio (PSNR); both are referred to differences between each pixel of original and reconstructed image and are defined as following:

$$MSE = \frac{1}{MN}\sum_{i=1}^{N}\sum_{j=1}^{M}[f(i,j) - \hat{f}(i,j)]^2$$

$$PSNR = 20 * Log(\frac{255}{\sqrt{MSE}})$$

where $f(i,j)$ and $\hat{f}(i,j)$ are, respectively, the transform coefficients before and after quantisation, while M and N are the number of pixels along image axes. The term 255 in PSNR formula derives from the fact that images with 8 bit/pixel have been considered.

Provided that a technique featuring optimum performance for all types of data cannot be defined, Marconi's study has defined those ones that best adapt to typical imaging sensors hosted on UAV: EO/IR sensors and SAR. The results are depicted following:

- JPEG: it is one of the most used techniques and it is based upon Direct Cosine Transform applied to square pixel blocks and subsequent quantisation of transformed coefficients.
  Advantages: this technique is highly standardised, allows fast compression/decompression and high compression rates (up to 25:1 with low optical quality degradation and PSNR). Also, it features minimum latency for real-time applications (compression can be applied as soon as all pixels belonging to a block are available, without waiting for the whole frame) and shows low sensitivity to BER (bits received uncorrectly affect only small image portions). Finally, a wide series of commercial dedicated hardware is available.
  Disadvantages: high compressed images presents the "blocking" effect, due to fact that single image portions are processed separately. This effect is particularly evident in low contrast images: therefore JPEG often give better results with EO images than with IR or SAR images.

- WAVELET: a suite of similar techniques is encompassed under this name, but not all are completely standardised; in general, they are based upon a recursive bidimensional Fourier-like transform of each frame; at each step, higher frequency are eliminated and lower frequencies are undersampled, thus performing compression.
  Advantages: wavelet techniques shows high efficiency, allows high compression rates (up to 30:1 with low optical degradation) and less distorsion on low contrast images ("blocking" effect is not present).
  Disadvantages: unfortunately, these techniques usually require high compression/decompression time due to algorithm complexity and introduce higher latency, because compression has to be performed over a whole frame at a time. Moreover, resolution of small objects can be reduced, since contours appear as "smoothed" at high compression rates, and a high sensitivity to BER must be taken into account (errors on received data flow can have destroying effects on the whole reconstructed image). Finally, less commercial dedicated hardware is available (many high efficiency algorithm have been identified, but their practical implementation is difficult).

In Figure 1 to Figure 6 some examples of JPEG and Wavelet compression effects on IR and SAR images are presented: they are extracted from our feasibility study realised for Alenia Difesa - Italy in July 1998. "Blocking" effect does not assume particular importance in Figure 2 (JPEG compressed), since the image has a high contrast; therefore, no significant differences can be pointed out with respect to Figure3 (compressed with Wavelet transform). On the other hand, blocks are clearly visible in Figure 5, where a high compression ratio has been used on a low contrast SAR image, while Figure 6 appears better at a direct observation. This does not necessarily mean that an Automatic Target Recognition (ATR) algorithm would work better on Wavelet compressed images, due to the "smoothing" effect clearly visible in both Figure3 and Figure 6. Furthermore, a comparison between compression/ decompression times (for non-real time algorithms running on Silicon Graphics' Indy™ workstations equipped with R4400/200 MHz processor and 32 Mbyte RAM) and between distorsion parameters (PSNR and MSE) is presented in Table 1. It is apparent that JPEG algorithm allows much faster coding and decoding than Wavelet; on the other hand, MSE and PSNR are comparable: it has been verified that MSE is typically slightly better for JPEG, while Wavelet works better in terms of PSNR.

In the end, both techniques are theoretically able to accomplish all data rate requirements indicated in Sec.5.2.3, provided that compression ratio is suitably limited. A maximum compression ratio of 15:1÷20:1 can support the most part of sensors likely to be hosted on a UAV while maintaining a satisfactory image quality level (even if usage of ATR algorithms is required). At the moment, JPEG still seems to allow easier implementation than Wavelet and has better overall performances for real-time applications; nevertheless Wavelet is open to improvement in the near future.

5.2.5 *MULTI-SENSOR CAPABILITY AND EXTERNAL INTERFACES*

Transmission of EO, IR and MTI sensor data has already been implemented in Marconi's Data Link for CATRIN-SORAO programme, even if in different HW configurations. Current aim is to accomplish, as far as possible, the requirements listed in Sec. 4.2 and 4.8 through a ADT and GDT configuration, capable to operate with one or more standardised sensors of different type at the same time and ensuring maximum payload interoperability and interchangeability.

A possible solution is to introduce on both ADT and GDT terminals a standard interface such as Fast Ethernet supporting a standard network protocol such as TCP/IP: this configuration provides a high speed connection (up to 100 Mbit/s) virtually independent from data format and relatively simple to to be implemented via a standard copper medium (single/double twisted pair). Moreover, Fast Ethernet is a widely diffused interface and many manufacturers of COTS HW can be found on the market: this could be helpful if cost reduction is required. Both EO, IR, MTI and SAR sensors can be supported, possibly in a single or multiple configuration, provided they are also equipped with a compatible interface and they are connected onto a dedicated bus. The only limitation is due to maximum bit rate: for instance, in case of multi-sensors configuration, overall throughput must be subdivided among users; also, a bit rate reduction factor related to bus collisions must be taken into account. TCP/IP protocol guarantees data multiplexing at the ADT end and data demultiplexing at the GDT end.

With reference to ADT architecture, when higher data rates are required, a dedicated point-to-point connection between the ADT and the sensor can be preferable to optimize data exchange. Alternatively, a fiber optic connection such as FDDI can be suggested; interfaces on copper media such as Gigabit Ethernet still relies on commercial HW only, thus do not appear as a suitable choice for a airborne military application. Similar considerations can be made for GDT architecture.

Finally, to maintain compatibility to non-standard output sensors and to commonly employed data bus, it is advisable to take provision for installation of some analog/digital interfaces: for instance, ARINC 429 and MIL-STD-1553 interfaces can be introduced to allow digital connections up to 100 Kbit/s and 1 Mbit/s respectively (e.g. for Command&Control data communications between FMS and ADT or between Ground Control Station and GDT); CCIR BW 625/50, RS170 or CCIR PAL colour video interfaces can be introduced to maintain compatibility to analogue output EO and IR sensors. In this context, a possible implementation scheme is represented by a MIL-STD-1553 connection between FMS, ADT and payload control system plus a Fast Ethernet connection between ADT and a high speed sensor for data transmission. Of course, contemporary use of different interfaces requires the resulting overall data rate to remain within the channel constraints.

5.2.5.1 *SAR sensors*

For SAR sensors, some particular considerations are required. Two possible architectures can be suggested for UAV applications (see ref. [1]): SAR sensors with on-board pre-processing, (i.e. able to exploit raw data on UAV and prepare a synthetic image to be transmitted through the datalink) and SAR with ground processing . In the latter case, the raw data flow produced by a SAR has to be transmitted through the datalink channel at a typical bit rate over some hundreds of Mbit/s, therefore exceeding Fast Ethernet throughput (even for a peer-to-peer connection between sensor and ADT). Moreover, only lossless compression techniques can be employed at low data compression ratio (see Sec. 5.2.4): in fact, due to the particular structure of raw SAR data and their intrinsic uncorrelation, synthetic image reconstruction can be difficult (if not impossible) in case of information losses caused by compression or by errors at the demodulator. Therefore, for UAV applications a on-board processing SAR is highly recommended whenever SWP constraints can be overrided.

5.2.6 *DATA LINK INTEGRITY - SAFETY ISSUES*

Reaching BER levels as low as those required for safety critical flight phases can limit significantly the data link performance: application of forward error correction techniques could require complicated encoding/decoding schemes, while simpler repetition techniques can easily lead to unacceptable transmission delay. In both cases, a lot of redundancy is added to the data flow to be transmitted through the radio channel, thus reducing the net bit rate available. Moreover, latency and update rate are generally a major issue when speaking about safety critical data transmission: e.g., for the operator control to be effective during UAV takeoff and landing, update rates up to 50 Hz can be required and latency must be contained within few tenths of milliseconds. On the other hand, SWP considerations suggest a Time Division Multiplex (TDM) architecture to minimise terminal size and weight, as already described in [1]; such an architecture allows a more flexible link management too, by assigning a different number of timeslot to downlink or uplink depending on actual communication needs. Therefore, two opposite requirements come out: a TDM datalink would better perform sensor data transmission and additional functions such as relay and multi user communication (see Sec. 6.1.1 and 6.3.3) but each terminal should switch too frequently between TX and RX states to satisfy update rate needs. Alternatively, a datalink based on Frequency Diversity (FD) on uplink and downlink would minimise latency and transmission delay on both direction but would require more complicated terminals and worsen ECCM characteristics due to operational band reduction. A compromise solution is not foreseeable within this limits: a better approach consists in using a TDM Wide Band Data Link (WBDL) to transmit sensor data and UAV/payload Command&Control data (when they are not safety critical); an additional Narrow Band Data Link (NBDL), based on FD architecture, can then be introduced to transmit all safety critical data requiring a high integrity level. The NBDL can also provide for secondary functions such as ATC voice relay (see Sec. 5.2.10) and handover management in case of multiple UAVs operations. Since data rate to support can be limited to a hundred of Kbit/s, NBDL can operate at considerably lower frequencies than WBDL, e.g. in the VHF/UHF band: this allows for much lower propagation losses and large link budget margin even for limited transmission power. Since critical flight phases such as takeoff and landing usually take place within a limited distance from the GDT (say less than 30 Km), a very low BER can be guaranteed.

5.2.7 *ECCM PROTECTION*

Military UAVs usually require a high jamming resistance capability: this feature can be achieved through Spread Spectrum ECCM techniques. A comparison between Frequency Hopping (FH) and Direct Sequence (DS) techniques is presented in [1], where advantages of FH are underlined. Generally, frequency changes ("hops") can be performed according to a pseudo-random sequence or according to a deterministic sequence: the latter technique is better identified as "Frequency Agility".

Pseudorandom Frequency Hopping ensures higher jamming resistance because the jammer, in order to achieve maximum effectiveness through narrow band emission, must reconstruct the frequency pattern; this is possible only by knowing the pseudorandom sequence generation law. On the other hand, this technique requires a quite complex handshake between terminals during link initialisation phase, thus possibly introducing synchronisation delay in case of temporary link loss. Conversely, Frequency Agility implies a slight reduction in jamming resistance (depending on the complexity of the deterministic hop sequence) but allows for a simpler synchronisation mechanism: this is a major issue when multiple terminals synchronisation is required, e.g. when the UAV is used as a relay platform (see Sec. 6.1.1) or as a communication router. (see Sec.6.3.3).

5.2.8 *DATA PROTECTION*

Data protection becomes mandatory when UAVs are used in a hostile environment and are subject to possible threats. However, some distinctions have to be made: generally, encryption of all information related to enemy field can be considered useless, if not detrimental. In fact, with this approach, every user is forced to employ a decryption unit to exploit data (see Sec. 6.1.1 and 6.3.3). On the other hand, a high security level could be required for UAV Command&Control data only (navigation parameters, flight plan, etc.) and intelligence data (e.g. when the UAV is used as a relay platform, see Sec. 6.1.1). These selected data typically require a limited transmission rate (from some tenths of Kbit/s to about 1 Mbit/s): using private key scramblers as encryption/decryption devices, no redundancy is introduced, so that protected data bit rate can still be considered a small amount of overall bit rate. To allow an easy change of scrambling keys, a Datalink architecture based on a separate encryption module (EM) is recommended and two possible connection schemes can be depicted (in the following we will refer to ADT architecture; these cosiderations can be easily extended to GDT architecture). In the first case, selection of data to be encrypted/decrypted is made inside the ADT, data are sent to the EM through a proprietary interface, processed and then sent back to the same terminal to be transmitted over the datalink (encrypted data) or to be assigned to user interfaces (decrypted data). This architecture avoids introduction of new interfaces towards FMS but implies a heavier internal ADT processing and requires more complicated control protocol (FMS must communicate to ADT which data must be protected and which not). Alternatively, data to be scrambled can be selected at the origin by FMS and, if necessary, sent to the EM; the latter is connected to the ADT through a proprietary interface; encrypted data are then managed inside the same terminal as they were coming from one of the additional interfaces described in Sec. 5.2.5. For data decryption, a similar process can be depicted. This solution presents some advantages: ADT internal processing is simplified while FMS needs only to redirect data to be protected to a different interface when encryption is required; if no data protection is needed, data can be sent to ADT via the usual Command&Control interface and the ADT to EM interface can be simply inhibited. Moreover, if the EM is equipped with a Fast Ethernet interface, as indicated in Sec. 5.2.5, it can be connected to the common bus and be addressed by the FMS as a general user: in this case no dedicated FMS to EM interface is required. This architecture is included in the general block schemes for ADT and GDT represented in Figure 7 and Figure 8.

5.2.9 *ADT ANTENNA CONFIGURATION*

At present, several UAVs use vertically polarised directive antennas mounted onto a steerable platforms. Commonly employed horn antennas feature an elevation beamwidth of some tenths of degrees in elevation plane and are steerable only in azimuth plane. However, it can be easily verified that antennas with wider elevation lobe (say 100 degrees or more) would improve system performance by allowing UAV larger attitude angles (pitch and roll) without link losses due to pointing mismatch. A simple horn with larger half-power lobe would excessively reduce the link operational range; therefore, three alternative architectures can be suggested:

- antenna unit equipped with two horn antennas instead of a single one: each horn is mounted with an opposite tilt angle with respect to UAV horizontal plane and can be selected separately accordingly to attitude angles relative to GDT antenna. The two horns are then jointly steerable in azimuth plane. Therefore, the "composite" elevation beamwidth can be widened up to 2 times that featured by a single horn, while azimuth coverage and RF gain are still guaranteed;
- antenna unit equipped with a single horn antenna mounted onto a 2-axis stabilised platform;
- antenna unit equipped with a synthetic aperture antenna (phased array) mounted on an azimuth steerable platform.

The first solution allows usage of rugged standard horns, thus limiting development costs of these parts, and permits a relatively simple antenna unit control: a discrete signal for "upside" or "downside" antenna selection is added to azimuth steering control. On the other hand, a branching waveguide section and a switching unit to be mounted onto the mobile part of the steerable platform are needed, thus increasing size and RF losses with respect to the single antenna solution. Moreover,

only elevation pointing mismatches can be recovered, but not depolarisation effects.
The second solution allows a complete recovery of every pointing and depolarisation mismatch but requires a sophisticated stabilisation and pointing system, thus increasing size and weight and complicating antenna unit control (antenna pointing and platform position must be determined in real time accordingly to mutual positions of ADT and GDT and to the UAV attitude angles).
The third solution is, potentially, the more flexible: phased arrays can be very light and offer static control of lobe direction. However, some further considerations are necessary: for instance, using three fixed arrays, a minimum 140 degrees lobe excursion in azimuth plane would be necessary to achieve RF coverage in all directions on the same plane and ensure a suitable superposition of operational angles for each antenna unit (thus avoiding spurious switching between antenna units at the separation edges). Performing such a wide lobe excursion is not a trivial task: main lobe enlargement, side lobe level increase and cross-correlation components strenghtening must be limited by carefully controlling each array element, therefore an accurate antenna unit design and simulation phase is required. A simplified approach consists in mounting each phased array on a azimuth steerable platform and electronically controlling the lobe direction only in the elevation plane, possibly at discrete steps, thus eliminating pointing mismatches due to UAV attitude angles.
In conclusion, the first solution appears as the best compromise when costs have to be reduced and limited UAV performances are required in terms of operational manoeuvres (speed, turn radii and climb/descent rates).
The second one allows the largest attitude angles, but is probably the more expensive. By the way, it can become mandatory when the link must be maintained locked while the UAV executes manoeuvres at roll/pitch angles higher than 25-30 degrees, especially at a limited distance from the GDT (i.e., few tenths of kilometres). These conditions are typically verified when a UAV travelling at medium-high speed (say, over 250 knots) performs a turn with a radius lower than 10 Km.
The third solution presents intermediate advantages, featuring good coverage performances but requiring higher development costs.

5.2.10 *INTEGRATION WITH ATC/ATM*

At present, in many countries UAV flight is limited to restricted military area only. These rigid limitations should be loosen in the next future, but, in order to operate an UAV over civil areas or, in general, outside reserved spaces, interaction with ATC is mandatory. Due to lack of specific regulations, it is logic to extend present ATC rules to UAVs; the latter can be considered equivalent to a manned aircraft whose crew is not really hosted onboard, but is located at the Ground Control Station. Since it is unforeseeable to change communication standards and equipment at the ATC side, the Data Link system must provide for all necessary functions to establish a link between the "remoted" crew and the ATC centre.
In other words, the Airborne Data Terminal (ADT) must operate as a bidirectional Relay platform for voice communications between the crew at Ground Station and the ATC operator: therefore, the ADT needs to be integrated to a suitable communication device (ATC terminal) capable to establish a connection with ATC (e.g. a VHF radio). Moreover, the ADT must be equipped with an analog-to-digital and digital-to-analog voice conversion unit to convey the ATC operator's voice onto the Data Link channel and reconvert the UAV pilot's voice into analog form before trasmission towards ATC. A similar function must be implemented at the Ground Control Station. The data rate requested can be relatively low (e.g. 2.4 Kbit/s for good quality compressed data) but must be taken in account when a Narrowband Data Link is used for the voice transmission (see Sec.5.2.6).
Integration with future ATM systems is much more complicated, due to the variety of messages that should be exchanged between UAV and ATM ground centres and the required higher integration level between the Data Link system and the whole Airborne Navigation System. A dedicated processing/interface unit must be designed to allow functional interconnection between Data Link system and one ore more ICAO standardised equipment for ATM, that is Mode-S transponder, VHF Data-Link (VDL) and Narrowband Satcom Data Link.

6. PROPOSED DATA LINK ARCHITECTURE

Accordingly to NIAG SG53 recommendations, a suitable UAV communication system capable to satisfy the above requirements can rely on a double Data Link architecture: a Wide Band Data Link (WBDL), whose primary functions are sensors data trasmission and aircraft/payload Command and Control, broadcasting and communications relay, and a Narrow Band Data Link (NBDL), whose primary function is to enhance Data Link integrity during safety critical flight phases.
To ensure maximum flexibility, a variety of interfaces towards external communications systems is also included. Sec. 6.1 presents the main WBDL features, Sec. 6.2 those of NBDL, while in Sec. 6.3 are depicted all the additional functions/characteristics that can be optionally included to satisfy all new requirements.

6.1 WBDL Main characteristics

6.1.1 *WBDL DATA LINK FUNCTIONS*

To fulfil long range (see Sec. 4.1) and communications requirements (see Sec. 4.3) the WBDL will perform three functions:

- a **point-to-point link**: it ensures connection between a main Ground Data Terminal (GDT) - equipped with a highly directive tracking antenna for long range operations and a medium gain steerable antenna for close-in operations - and the Airborne Data Terminal (ADT) - equipped with two or three selectable, medium gain steerable antennas. The point-to-point link is bi-directional and performs sensor data transmission to the GDT (downlink) and UAV/payload Command&Control during normal flight (uplink).
- a **broadcast additional link**: it ensures connection between the ADT and one or more GDT or Portable Ground Data Terminal (PGDT) (see Sec. 6.3.2). A omnidirectional antenna mounted onto the UAV can be activated and fed with the same signal sent through the point-to point data link, thus realising the sensor data dissemination function over a large territory. In this case, the broadcast link is merely unidirectional, that is no handshake is considered between ADT and GDTs/PGDTs.

- a **data relay function**: this feature can be useful to overcome line-of-sight constraints in case of OTH missions or in presence of natural obstacles along flight path: a Relay ADT (RADT) act as a signal repeater between the mission UAV and the GDT. From the communications point of view, this function can be seen as a particular case of the preceding item if we consider that the RADT acts as a router between only two users. In practice, some differences are to be considered: for instance, to maintain a suitable operational range, the RADT will use the airborne steerable antennas (and not the omnidirectional one) to establish links towards both GDT and mission UAV. Moreover, the GDT must be able to manage both RADT and mission UAV/payload Command&Control data and those data must be multiplexed and transmitted along with sensor data.

6.1.2 *WBDL OPERATIONAL FREQUENCY*

Accordingly to NATO/CEPT recommendations, the WBDL should operate in J band (14.62 - 15.23 GHz): in fact this band is defined as following:

- NATO Harmonised Band type 1 (i.e band in general military use in NATO)
- "essential military required for fixed/mobile military systems" (i.e. its unavailability would have effects on operativity of NATO forces)
- recommended for UAV Command&Control and real-time trasmission of images.

6.1.3 *WBDL DATA LINK MANAGEMENT*

As indicated in [1], the WBDL better performs its functions operating on a Time Division Multiplex basis to accomplish SWP constraints. This architecure also allows a SW dynamic allocation of timeslots on downlink and uplink, thus sharing the overall bit rate on the two directions in order to accomplish different functions as data relay (see Sec. 6.1.1) and communications within a tactical network (see Sec. 6.3.3)

6.1.4 *WBDL OPERATIONAL RANGE AND DATA RATE*

As described in Sec. 5.2.1, operational range is a function of a variety of parameters including GDT and ADT antenna gain, EIRP and bit Rate. A suitable configuration features a high gain GDT antenna (a medium-high gain PGDT antenna) and up to three elevation fixed, azimuth steerable ADT antennas. Moreover, accordingly to considerations depicted in Sec 5.2.3, a data rate selection capability can be useful to optimize perfomances depending on actual needs. For example, two possible data rates can be proposed: a speed of about 2.5 Mbit/s can be used when medium data rate sensors are employed, thus extending ranges up to 200 Km with solid state RF amplifier or up to 250 Km with small vacuum tube RF amplifier. The transmission speed can then be switched up to 12 Mbit/s when high data rate sensors are used: in this case the operational range must be reduced at about 125Km and 150 Km respectively.

6.1.5 *WBDL BIT ERROR RATE*

The link budget should be designed to guarantee a Bit Error Rate (BER) of about 10^{-3} - 10^{-4} for raw data; such a figure can be considered good for data produced by typical imaging sensors. A lower BER value (such as 10^{-7}) will be obtained on selected data (typically Command&Control data and intelligence data) through forward error correction techniques: cyclic codes such as Golay and BCH classes, associated to interlaeaving/deinterleaving modules appears as a good compromise among coding efficiency, error bursts recovery, bit rate increase and implementation complexity.

6.1.6 *ECCM PROTECTION*

Accordingly to considerations indicated in Sec. 5.2.7, Frequency Agility techniques ensure a suitable jamming robustness associated to a multi-user synchronisation capability for relay and communications purposes.

6.1.7 *MULTI-SENSOR CAPABILITY AND EXTERNAL INTERFACES*

Both ADT and GDT can be equipped with a standard Fast Ethernet interface and use TCP/IP as network protocol: this enhance interoperability and allows multi-sensors operations by permitting sensors connection to a common bus. To extend interoperability to present sensors equipped with analogue interfaces and to widely used data bus, ARINC429, MIL-STD1553 digital interfaces and CCIR 625/50, RS170 and CCIR PAL analogue video interfaces can be optionally included.

6.1.8 *DATA COMPRESSION*

JPEG data compression with compression ratio up to 15:1÷20:1, selectable by user at discrete steps depending on image resolution/quality desired, appears as the best choice

6.1.9 *DATA MULTIPLEXING-DEMULTIPLEXING*

In order to perform all their functions, ADT and GDT must have respectively data multiplexing and demultiplexing capability. Data multiplexing is performed at ADT by Fast Ethernet bus (see Sec. 6.1.7), that allows multiple users connection with different TCP/IP addresses. A further, internal data multiplexing level is introduced to allow transmission of data from supplemental interfaces (video, MIL-STD1553, etc.) and from encryption module (see Sec. 6.1.10). Similarly, at GDT, data coming from datalink are internally demultiplexed and sent to Fast Ethernet interface, supplemental interfaces (if present) and encryption module. A further data demultiplexing is performed on Fast Ethernet bus via different TCP/IP user addresses.

6.1.10 *DATA ENCRYPTION*

To ensure data security, both ADT and GDT can be equipped with an external encryption/decryption module to be connected as in Figure 7 and Figure 8.

6.1.11 *WBDL ANTENNAS*

The proposed architecture uses a highly directive, reflector type steerable antenna with precision autotracking capability (based on monopulse technique for azimuth tracking and power derivative technique for elevation tracking). For close-in operations, a secondary horn antenna is mounted over the main one and performs its functions in parallel. Both antennas operates in vertical polarisation. The GDT Antenna mount hosts the Radio Frequency Unit and the RF power amplifier (see Sec. 6.1.4). Moreover, a tilt sensing unit is incorporated for mount attitude angles compensation.
The ADT Antenna units must be chosen accordingly to specific UAV requirements, as indicated in Sec. 5.2.9. By the way, usage

of a double horn antenna unit appears more probable, even if a feasibility study for a patch array antenna unit is in progress.

6.2 NBDL main characteristics

6.2.1 *NBDL FUNCTIONS*

As introduced in Sec.5.2.6 and Sec.6, NBDL main function is the redundant transmission of UAV Command&Control Data in order to achieve high integrity for safety critical flight phases; moreover, NBDL can act as an emergency link in case of failure of the WBDL, thus allowing UAV control until the end of the mission. The NBDL also support the ATC relay function and can be optionally used to manage handover when a UAV has to be controlled by two GDTs or to ensure connection to multiple UAVs.

6.2.2 *NBDL OPERATIONAL FREQUENCY*

Accordingly to NATO ARFA recommendations and considerations depicted in Sec. 5.2.6, NBDL could operate in the VHF/UHF band from 230 to 400 MHz. Use of higher frequencies can be considered accordingly to data rate requirements (see Sec. 6.2.4).

6.2.3 *NBDL DATA LINK MANAGEMENT*

In order to guarantee high update rate and low latency, the NBDL uses a Frequency Diversity technique to transmit over downlink and uplink (see Sec. 5.2.6)

6.2.4 *NBDL OPERATIONAL RANGE AND DATA RATE*

The NBDL can operate at distances up to 150 Km at data rates between 25 and 500 Kbit/s by using ground and airborne omnidirectional antennas. The definite data rate value must be chosen accordingly to actual needs: both UAV Command&Control function and additional functions such as ATC voice relay, when required, must be. If the range has to be increased, usage of a GDT directional antenna must be considered.

6.2.5 *NBDL BIT ERROR RATE*

The link budget is dimensioned to achieve a BER level of about 10^{-4} for raw data. Through Forward Error Correction Techniques, the actual data rate is cut down to 10^{-8}-10^{-9}, thus a good value to ensure suitable UAV control even during critical flight phases.

6.2.6 *ECCM PROTECTION*

For NBDL a dedicated Frequency Hopping technique is advisable to enhance its ECCM protection level. Standard hopping protocols, such as HAVEQUICK or SATURN can be considered to increase interoperability.

6.2.7 *NBDL INTERFACES*

The NBDL features a dedicated interface to the corresponding WBDL terminal that support both NBDL Command&Control data and transmission data.

6.3 Data Link system extensions

6.3.1 *INTERFACES TO EXTERNAL COMMUNICATIONS EQUIPMENT*

In order to fulfil all requirements indicated in Sec. 5.2.10 and allow the integration with Command&Control standardised Data Links (e.g. LINK16) and SATCOM devices, an additional module called Data Link Interface Processor (DLIP) can be introduced, as indicated in Figure 7 and Figure 8. This module is connected to the WBDL through an additional interface and performs all data processing functions necessary to convey information from the auxiliary communication systems to the WBDL and viceversa. For instance, it can encompass an autonomous CPU plus a vocoder for ATC relay function, a serial interface to communicate with the SATCOM terminal and so on.

6.3.2 *PORTABLE GDT (PGDT)*

To exploit all Data Link functions, including broadcasting and relay (see Sec. 6.1.1) and communication routing (see Sec 6.3.3), a portable GDT (PGDT) can be added to standard Data Link configuration. The PGDT has nearly the same function of GDT, even with reduced performances. It is based on three functional units: a RF/processing unit (RFPU, with size and weight similar to ADT), an Antenna Unit (AU) and a Data Exploitation Unit (DEU). A block scheme is depicted in Figure 9.

The RFPU unit provides for the following functions: RX/TX, modem, data multiplexing/demultiplexing. It is equipped with the same interfaces of GDT: in particular, a Fast Ethernet interface is used for connection to the DEU. If necessary, both DEU and RFPU can be connected onto a common bus.

The AU is based on a medium gain reflector antenna with steering capability in azimuth and elevation planes and is mounted on a ruggedized mast. It is equipped with tilt sensors to compensate for mount attitude angles and with a GPS plus a magnetometer device for geodetic position self-determination. The AU can be pointed accordingly to data provided through the DEU or via external interface. Once the link is locked, UAV tracking is ensured thanks to a power derivative algorithm in both azimuth and elevation planes; if required, tracking can be based upon telemetry data sent by the ADT.

The DEU is a small portable unit to be connected to the RFPU via a Fast Ethernet interface: it is equipped with a monitor for sensor data visualisation and AU/ RFPU control. The DEU also allows to reconfigure the PGDT to be used in the Tactical Network mode (see Sec. 6.3.3).

Finally, the DEU can be omitted and the RFPU can be connected directly to a Ground Station similar to that used for the GDT.

6.3.3 *WBDL COMMUNICATION FUNCTION - TACTICAL NETWORK*

If required, both ADT, GDT and PGDT (see Sec. 6.3.2) can be SW reconfigured to define a local tactical communication network: in this context, the ADT act as a communication router between up to 8 ground users (i.e. the GDT and up to 7 PGDT) on a Time Division Multiplex basis; each user can be assigned a variable number of timeslots, depending on its transmission and reception bit rate needs, provided that the overall bit rate available is not exceeded. In this case each connection is bi-directional and point-to-multipoint or multipoint-to-point communications are possible. PGDTs are connected to the ADT via the airborne omnidirectional antenna, while the airborne steerable antennas are used to ensure the link to GDT;

UAV/payload Command&Control functions still rely on ADT-GDT link.

7. ACKNOWLEGMENTS

The authors wishes to acknowledge the Italian Ministry of Defence for their interest and Mr. Ugo Squillari and Mr. Lorenzo Carbonini of Marconi Communications - Genoa - Italy for their precious contribution.

8. REFERENCES

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IR IMAGE

SAR IMAGE

Figure 1 (original)

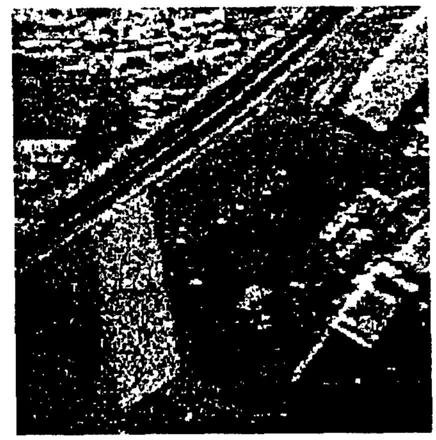

Figure 4 (original)

Figure 2 (JPEG compression 25:1)

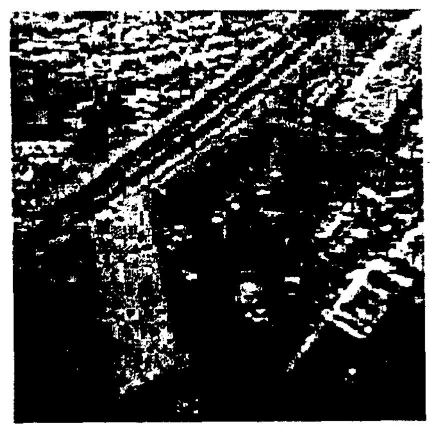

Figure 5 (JPEG compression 30:1)

Figure3 (Wavelet compression 25:1)

Figure 6 (Wavelet compression 30:1)

Image	Compression type/ratio	Coding time (sec)	Decoding time (sec)	MSE	PSNR (dB)
Figure 2	JPEG 25:1	0.6	0.3	79	29.15
Figure 3	Wavelet 25:1	32.8	8	95.3	28.33
Figure 5	JPEG 30:1	0.4	0.2	44.3	31.6
Figure 6	Wavelet 30:1	32.1	8	50.3	31.1

Table 1

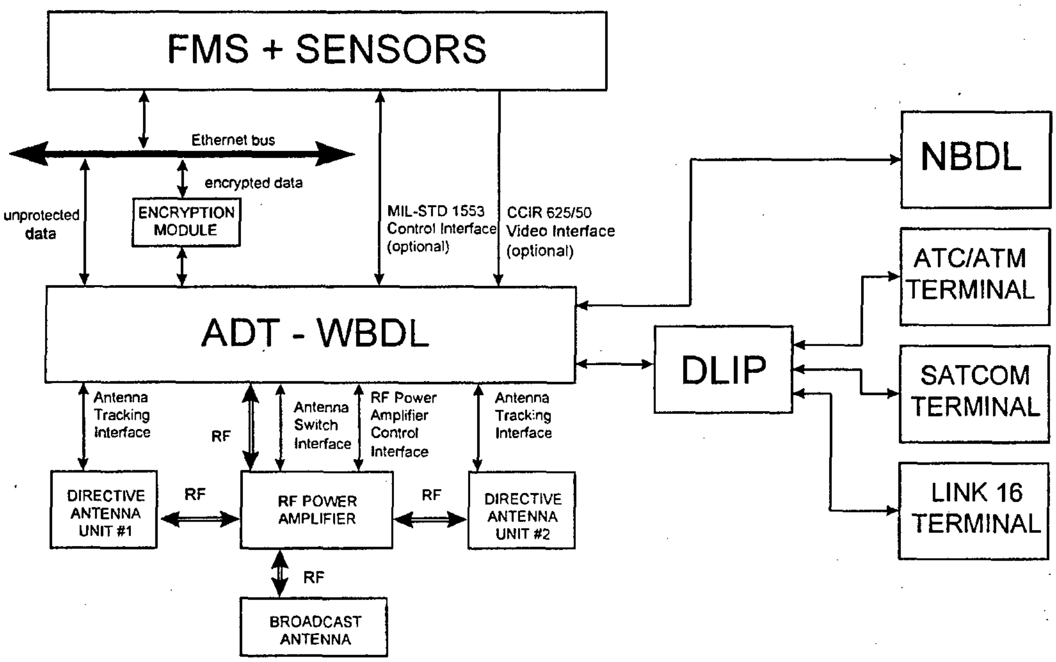

Figure 7

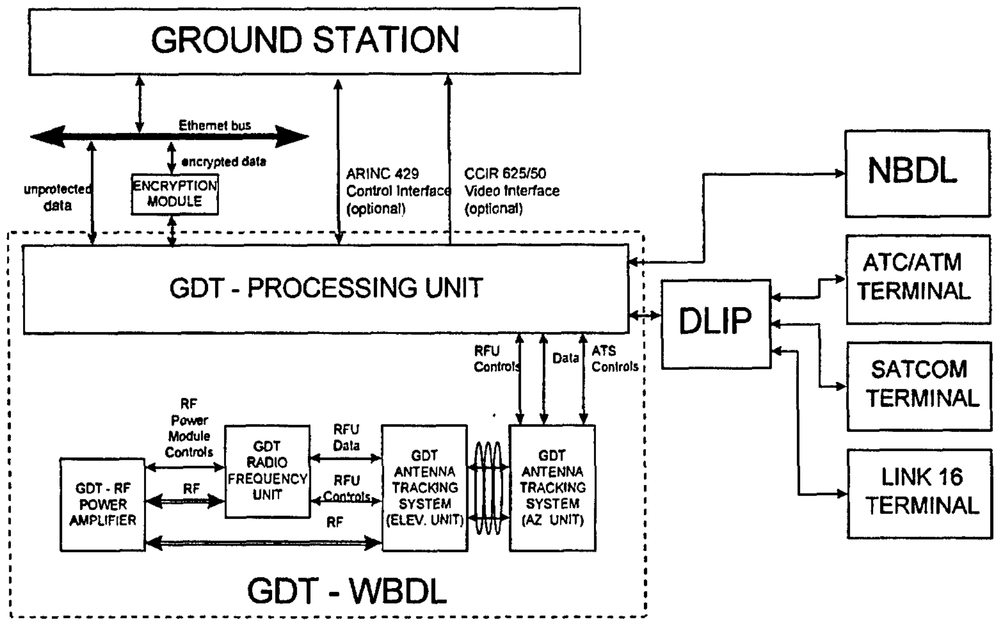

Figure 8

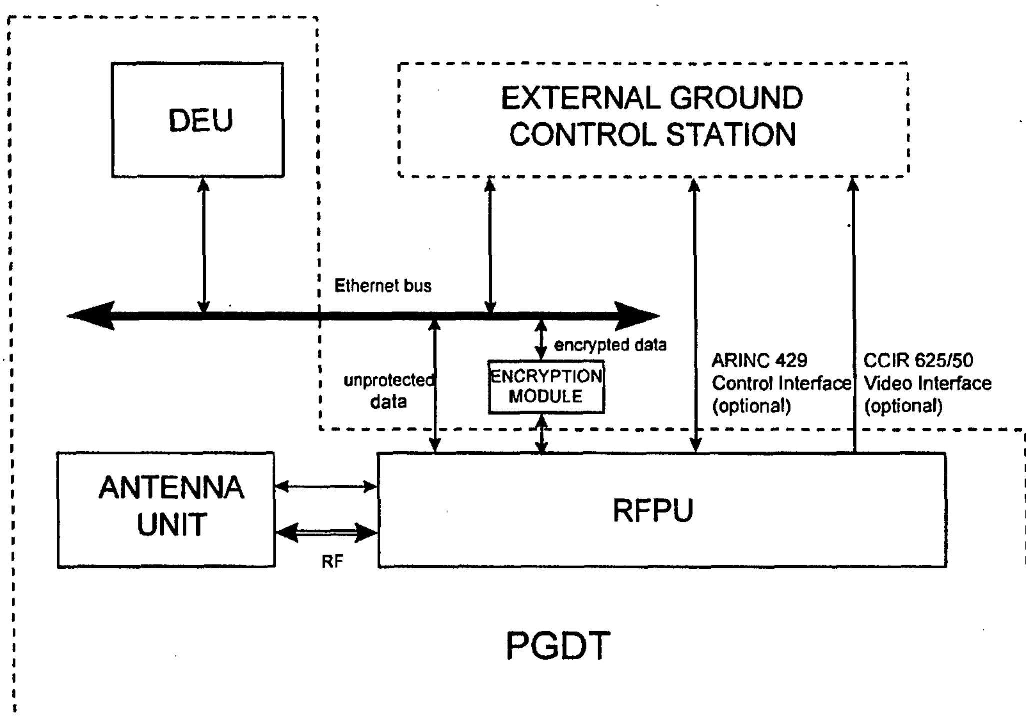

Figure 9

Signal Processing for Micro Inertial Sensors

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Abstract: In the development of the guidance and control packages for unmanned vehicles, it is highly desirable to have inertial measurement sensors which are small, inexpensive, low power, reliable and accurate. New technological advances in the design and construction of micro inertial sensors, such as accelerometers and gyroscopes, have much promise in providing small, inexpensive, and low power devices; however, much improvement in the reliability and, especially, the accuracy of these micro devices is still necessary. Further major improvements in these two properties will probably not be accomplished in the near future, thus it will be necessary to use special signal processing methods to provide the accuracy. One way which has been proposed to improve the accuracy, and concurrently the reliability, of micro sensors is to use many, perhaps one hundred or more, micro sensors on a single chip (or a few chips) and using statistical methods to combine the individual outputs of these sensors to provide an accurate measurement. One method of performing such a combination is through an extended Kalman filter (EKF). A standard application of an EKF to an array of gyroscopes would involve at least six state equations per gyroscope and the number of covariance equations would be in the order of the square of the product of six times the number of gyroscopes. Obviously, the 'curse of dimensionality' very quickly limits the number of sensors (gyroscopes) which can be used. Even if the EKF for each individual gyroscope is uncoupled from the rest, the number of covariance equations is of the order of the number of gyroscopes times six squared. This can still lead to a formidable computational burden. In this paper, a new technique of applying an EKF to this problem of combining many sensors is proposed. By using the common nominal model for each of the micro sensors and developing a single EKF, improved accuracy is achieved by a single EKF with the dimension of one sensor. For cases in which the micro sensors are corrupted by correlated noise (between the sensors) an artificial neural network could be added to the EKF dynamics to track the noise. Simulated examples will be discussed.

Summary: Recent advances in the technology of microelectromechanical systems (MEMS) has led to optimistic predictions of the potential applications of various micro devices. One family of devices which appears to have wide applicability in many areas is the family of inertial sensors, including gyroscopes and accelerometers. Micro-sensors, because of their small size, often have only moderate accuracy as compared to the accuracy of full-size sensors. Applications which demand sensors with small size and low cost as well as high accuracy, will require signal processing methods. Because of the expected low cost of the micro-sensors, one approach to increased accuracy is to use a large number of micro-sensors to measure the same quantity and then use statistical methods to combine the many low accuracy measurements to generate a single high accuracy measurement. For many years the extended Kalman filter (EKF) has been used to process output signals from inertial sensors to produce more accuracy than is possible from the raw output signals, thus it is natural to assume that the EKF can be readily adapted to the many micro-sensor problem. In this paper, a technique is proposed in which an arithmetic average of the many outputs from a set of micro-gyroscopes is input to a single average EKF. Under certain simple assumptions, this can be shown to produce the desired result. Using a model of a real micro-gyroscope this technique was simulated for a set of ten micro-gyroscopes and the preliminary results indicate that this method has promise. Continuing exploration of this method will include adaptive EKF methods using a neural network based EKF which will allow the filter to track correlated errors.

Introduction. Recent developments in micro-electromechanical systems (MEMS) technology have led to optimistic predictions for the use of micro devices in a wide range of applications. It appears that micro-sensors, in particular, have immediate applicability in many fields from medical implants to automobiles to aerospace vehicles. Small size plus their probability of becoming very inexpensive make their potential range of applications almost limitless. However, in spite of small size being a major advantage of micro-sensors, it can also be a major disadvantage. In particular, in many cases, the accuracy of a sensor can be controlled much easier if the sensor has large dimensions, because accuracy is often a function of dimensional ratios and controlling such ratios by machining is easier when dimensions are larger. On the other hand, if the micro-sensors can be made much more inexpensively than larger machined sensors then this disadvantage may be overcome by using many relatively inaccurate, but also inexpensive, sensors as opposed to one, or a few, accurate, but much more expensive, sensors. Note that the use of many micro-

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

sensors measuring the same quantity can also provide reliability through redundancy at a reasonable cost. This latter point, while of considerable interest, will not be considered in this paper. The problem of interest here is that of combining the outputs of several micro-sensors, all measuring the same quantity, so that the accuracy of the combination exceeds the accuracy of the individual micro-sensors but without requiring an extraordinary amount of computation. This is what will be referred to as the signal processing problem for micro inertial sensors.

The signal processing problem: A sensor is a device that measures a physical quantity and produces a corresponding output, typically an electrical quantity, which is related in a known way to the physical quantity. In practice, the measurement of the physical quantity is corrupted by noise and the relationship between the physical quantity and the corresponding output is corrupted by another noise. The accuracy of the sensor is dependent upon the magnitudes of these noises. The accuracy of a sensor might be improved by better understanding of the physics by which the sensor measures the physical quantity and how it produces the corresponding output and improving the process by which the sensor is manufactured or by applying appropriate signal processing techniques to the output signal. In the area of micro-sensors, significant accuracy improvements in the manufacturing process will require increased costs and/or larger geometries, both of which will tend to neutralize the advantages of such devices. Thus signal processing techniques applied to multiple sensor configurations are being examined and are expected to improve the accuracy of existing micro-sensors. This is not to imply that improved manufacturing processes are not being developed; however, currently, appropriate processing of micro-sensor outputs appears to be the quickest and most feasible method of improving sensor accuracy.

The simplest signal processing concept to improve micro-sensor accuracy is to manufacture one (or a few) chips with a total of many micro-sensors all of which measure the same physical quantity. The outputs of all of the micro-sensors are then simply averaged arithmetically. If the noises associated with the outputs of the several micro-sensors are additive, mutually independent and zero mean, then the standard deviation of the error of the arithmetic average is reduced by the square root of the number of output signals. Thus, if one hundred micro-sensors are used, it is equivalent to replacing them with a single micro-sensor with an error with one-tenth the standard deviation. However, if the errors in the output signals are non-zero mean (across the ensemble of micro-sensors) or if the errors are correlated across the micro-sensors, then arithmetic averaging may not be effective. That is, the averaging will reduce the uncorrelated component of the noise but may have little effect on the correlated component of the noise. A correlated component of the noise in the output signals is to be expected if many of the sensors are on a single chip. For example, any alignment errors in the chip manufacturing process may generate measurement errors in one micro-sensor which are strongly correlated with all of the measurement errors on the other micro-sensors. If the manufacturing process generates alignment errors which are correlated from chip to chip, for example all the chips come from a single wafer, then this correlation may extend to all of the micro-sensors. In this case, simple arithmetic averaging may not be effective as a signal processing technique.

In the application of a standard sized inertial sensor, it is quite common to process the output of the sensor through a Kalman filter, or more likely through an extended Kalman filter (EKF), to improve the accuracy of the measurement. If a number of inertial sensors, for example, three gyroscopes and three accelerometers, are combined on a single platform it is common that a single extended Kalman filter is used to generate estimates of the state of the platform on which the sensors are mounted. These estimates are generally much improved over the measurements which are taken directly from the sensors. A similar concept could be used to generate an estimate of the common quantity being measured by the many micro-sensors. In particular, micro inertial sensors have well developed mathematical models and are well suited to the application of an extended Kalman filter. The difficulty with applying this concept to a set of many micro inertial sensors is that the dimensionality of the EKF may become excessive. For example, if a single gyroscope is modeled by a set of six coupled dynamic equations, then six hundred equations would be needed to model one hundred gyroscopes. The resultant EKF which uses this dynamic model would have six hundred states and its covariance equation would have between two thousand and one hundred eighty thousand (180,000) equations depending upon the coupling between the various gyroscopes. Obviously, this method of combining measurements is limited by the number of micro gyroscopes which are being used.

The method proposed in this paper for combining the measurements from many micro-sensors is to first generate the arithmetic average of the outputs of the sensors and then process this average output through an average EKF. Consider the following standard Kalman filter problem of estimating the state of a system defined by the vector-matrix equation

$$\frac{d\mathbf{x}}{dt} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u} + \mathbf{w} \qquad (1)$$

where $\mathbf{x}$ is the system state vector, $\mathbf{u}$ is the system input vector, and $\mathbf{w}$ is a zero mean white noise vector with covariance $\mathbf{Q}$. $\mathbf{A}$ and $\mathbf{B}$ are the matrices which define the system. The state vector is measured through a noisy linear transformation

$$\mathbf{y} = \mathbf{C}\mathbf{x} + \mathbf{v} \qquad (2)$$

where $\mathbf{C}$ defines the transformation and $\mathbf{v}$ is a zero mean white noise with covariance matrix $\mathbf{R}$. Suppose that the system state can also be measured from a set of N other systems defined by

$$\frac{d\mathbf{x}_i}{dt} = \mathbf{A}\mathbf{x}_i + \mathbf{B}\mathbf{u} + \mathbf{w}_i, \quad i = 1,2,\cdots,N$$

where $\mathbf{x}_i$ is the state vector and $\mathbf{w}_i$ is the white noise vector of the ith system. The states of these systems are measured through a set of N measurement equations

$$\mathbf{y}_i = \mathbf{C}\mathbf{x}_i + \mathbf{v}_i, \quad i = 1,2,\cdots,N$$

where $\mathbf{v}_i$ is the white noise of the ith measurement. An arithmetic average of the outputs is formed as

$$\bar{\mathbf{y}} = \frac{1}{N}\sum_{i=1}^{N}\mathbf{y}_i = \mathbf{C}\left(\frac{1}{N}\sum_{i=1}^{N}\mathbf{x}_i\right) + \frac{1}{N}\sum_{i=1}^{N}\mathbf{v}_i$$

or

$$\bar{\mathbf{y}} = \mathbf{C}\bar{\mathbf{x}} + \bar{\mathbf{v}} \qquad (3)$$

Now averaging the N differential equations results in the average differential equation

$$\frac{d\bar{\mathbf{x}}}{dt} = \mathbf{A}\bar{\mathbf{x}} + \mathbf{B}\mathbf{u} + \bar{\mathbf{w}} \qquad (4)$$

In the stochastic sense equation (3) is identical to equation (2) and equation (4) is identical to equation (1), except that the noise $\bar{\mathbf{w}}$ has a covariance of $\mathbf{Q}/N$ and the noise $\bar{\mathbf{v}}$ has a covariance of $\mathbf{R}/N$. Thus if estimating the system response to the input $\mathbf{u}$ is of primary interest, the effect of the white noises is reduced if the average system output is used to drive the Kalman filter rather than the measurement in equation (2). In the following example, the problem of estimating the output of a set of ten micro-gyroscopes all measuring the same angular rate using a single EKF was simulated and compared with the method of applying ten EKFs with output averaging

Mathematical model of a micro-gyroscope: In this section, the mathematical model of a micro gyroscope is presented. The parameters used later in the simulation are taken from an actual experimental micro-gyroscope developed by Irvine Sensors, thus the simulation represents the real world as nearly as we were able to model it. The gyroscope is composed of a small rigid plate attached to a housing through a set of four thin orthogonal support wires. A set of orthogonal axes is fixed to the plate with the origin at the center of mass of the plate and the three axes are aligned with the principal axes of the plate. The x-axis and the y-axis lie in the plane of the plate and are assumed to be aligned with the support wires. In an application, the housing is attached firmly to a much larger rigid body (perhaps an automobile), thus the plate can rotate, to a limited extent, about all three axes relative to the housing and, thus also rotates relative to the larger rigid body. However, it is assumed that that any translation relative to the larger rigid body is negligible. Because the axes rotate with the plate, the products of inertia of the plate in this coordinate system are zero. The plate is forced to oscillate at a constant amplitude and frequency about the z-axis by a sinusoidal torque applied by an electric field. The x-axis is the input axis through which the input angular velocity of the large rigid body is coupled into the plate through the support wires. The y-axis is the output axis of the gyroscope from which a measurement of the input angular velocity is obtained as some function of the periodic motion induced about the y-axis by the angular motions about the x-axis and the z-axis. Under these conditions, Euler's equations of motion can be used to develop a dynamic model of the plate. The plate is symmetric in the x-y plane so that the moments of inertia about the x-axis and the y-axis are equal. The moment of inertia about the z-axis is much larger than these two. We define the angular position of the plate from its 'rest' position by the angles θ_x, θ_y, and θ_z measured about the x, y, and z axes. A sinusoidal torque, $T(t)$, is applied to the plate about the z-axis producing a periodic motion about the z-axis. The other torques about the z-axis are a damping torque and a spring torque, both due to the mechanical properties of the supporting wires along the x-axis and the y-axis. The applied torques about the y-axis and the x-axis are a damping torque and a spring torque due to the supporting wires and the damping coefficients and spring constants are assumed to be equal about each axis because of the symmetry of the plate in the $x-y$ plane. When the housing is rotated at an angular rate of Ω_x rad/sec about the x-axis, a torque $T_x(t)$ is transmitted to the plate by the support wires and consists of a damping torque and a spring torque

$$C_x(\Omega_x - \dot{\theta}_x), \quad \text{and} \quad K_x\left(\int_0^t \Omega(t')dt' - \theta_x\right)$$

where C_x and K_x are the damping coefficient and the spring constant about the x-axis. The input rate Ω_x induces a motion in the y-axis and Ω_x is determined from the measurement of the angular motion about the y-axis. Based on these conditions, Euler's equations can be written as

$$\ddot{\theta}_x + a_1\dot{\theta}_x + a_0\theta_x + A\dot{\theta}_y\dot{\theta}_z = a_1\Omega_x + a_0\int_0^t \Omega_x(t')dt'$$

$$\ddot{\theta}_y + a_1\dot{\theta}_y + a_0\theta_y - A\dot{\theta}_x\dot{\theta}_z = 0$$

$$\ddot{\theta}_z + b_1\dot{\theta}_z + b_0\theta_z = T_0\sin\omega_o t$$

where the coefficients are determined from the various physical parameters of the gyroscope. The desired output of the gyroscope is the input angular rate output $\Omega_x(t)$. This is obtained by measuring and processing the angular rate $\dot{\theta}_y(t)$.

Steady-State Operation: Assuming that the rate of change of the angular rate input $\Omega_x(t)$ to the gyroscope is slow relative to the rates of change induced by the applied torque $T_0 \sin\omega_0 t$ and that the nonlinear effects in the x and y equations are relatively small, phasor analysis can be used to determine a steady-state value of the output $\dot{\theta}_y(t)$ as

$$\dot{\theta}_y(t) = AT_0 G_z(\omega_0) G_y(\omega_0)\omega_0^2 \Omega_x \sin\omega_0 t$$

where

$$G_z(\omega_0) = \frac{1}{\sqrt{(b_0 - \omega_0^2)^2 + (\omega_0 b_1)^2}}$$

and

$$G_y(\omega_0) = \frac{1}{\sqrt{(a_0 - \omega_0^2)^2 + (\omega_0 a_1)^2}}$$

Note that the phase shift of the phasor is not needed and has been ignored. Note that this equation could be written

$$\dot{\theta}_y(t) = K\Omega_x(t)\sin\omega_0 t$$

where K is a constant. Thus $\dot{\theta}_y(t)$ is sine wave $\sin\omega_0 t$ modulated by the applied angular rate $\Omega_x(t)$. The angular rate can thus be obtained by a simple amplitude modulation (AM) demodulator.

State Equations for the Gyroscope: For a Kalman filter the equations for the gyroscope must be written in the form of state equations. To put the three equations into a state equation form, let

$$x_2 = \dot{\theta}_x$$

$$x_3 = \theta_y \qquad x_4 = \dot{x}_3 = \dot{\theta}_y$$

$$x_5 = \theta_z \qquad x_6 = \dot{x}_5 = \dot{\theta}_z$$

then the state equation representation for the gyroscope is

$$\dot{x}_1 = -a_0 x_2 + a_0 \Omega_x$$

$$\dot{x}_2 = x_1 - a_1 x_2 - A x_4 x_6 + a_1 \Omega_x$$

$$\dot{x}_3 = x_4$$

$$\dot{x}_4 = -a_0 x_3 - a_1 x_4 + A x_2 x_6$$

$$\dot{x}_5 = x_6$$

$$\dot{x}_6 = -b_0 x_5 - b_1 x_6 + T_0 \sin\omega_0 t$$

where the variable x_1 has no specific physical meaning. Two additional equations can provide a simple demodulation of the variable

$$x_4(t) = \dot{\theta}_y(t)$$

to generate $\Omega_x(t)$. These equations are

$$\dot{x}_7 = x_8$$

$$\dot{x}_8 = -c_0 x_7 - c_1 x_8 + c_0 x_4 \sin\omega_0 t$$

where the coefficients were chosen to provide low pass filtering with a corner frequency at $\omega_0/10$ rad/sec. The output measurement is now the modulator output, that is,

$$z(t) = x_7(t)$$

Ideally, in steady state, this is related to $\Omega_x(t)$ by the relationship developed in the steady-state section and the demodulator gain by

$$\Omega_x(t) = \frac{K}{2} x_7(t)$$

Design Coefficients. The design coefficients for the gyroscope simulated in this paper are

$$a_1 = 1.8621 \times 10^4$$

$$a_0 = 3.4483 \times 10^8$$

$$b_1 = 9.3750 \times 10$$

$$b_0 = 3.3750 \times 10^8$$

$$A = 4.5172$$

and

$$\omega_0 = 2\pi \times 3000 = 1.8850 \times 10^4 \text{ rad/sec}$$

which is near the resonant frequency of the linear part of the y-axis equation. The demodulator coefficients are

$$c_1 = 1200\pi \text{ and } c_0 = (600\pi)^2$$

The magnitude T_0 of the forcing function was chosen to be

$$T_0 = 1.5 \times 10^8$$

which generates a maximum steady state motion about the x-axis of a fraction of a radian. The resulting state equations using these coefficients was used as the 'truth model' for the simulations which are discussed later.

Kalman Filter Equations. To generate a set of Kalman filter equations, the following modification to the gyroscope state equations had to be made. Let:

$$\Omega_x = x_2 + n_1$$

where n_1 is the unknown difference between the input Ω_x and the state $x_2 = \dot{\theta}_x$. The resulting state equations can now be rewritten:

$$\dot{x}_1 = a_0 n_1$$
$$\dot{x}_2 = x_1 - A x_4 x_6 + a_1 n_1$$
$$\dot{x}_3 = x_4$$
$$\dot{x}_4 = -a_0 x_3 - a_1 x_4 + A x_2 x_6 + n_4$$
$$\dot{x}_5 = x_6$$
$$\dot{x}_6 = -b_0 x_5 - b_1 x_6 + T_0 \sin \omega_0 t + n_6$$

with the demodulator equations

$$\dot{x}_7 = x_8$$
$$\dot{x}_8 = -c_0 x_7 - c_1 x_8 + c_0 x_4 \sin \omega_0 t + n_8$$

The measurement equation is given by

$$z = x_7 + v$$

The quantities n_1, n_4, n_6, n_8 and v are random quantities which in the development of the extended Kalman filter (EKF) are assumed to be white noises. As almost four decades of usage has shown the EKF is robust to inaccuracies in the assumptions on the system noises. For convenience, the gyroscope model is now rewritten in the vector-matrix form:

$$\dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}) + \mathbf{G}\mathbf{n} + \mathbf{g}(\mathbf{x}) \sin \omega_0 t$$
$$z = \mathbf{h}^T \mathbf{x} + v$$

where

$$\mathbf{x} = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \\ x_6 \\ x_7 \\ x_8 \end{bmatrix} \qquad \mathbf{g}(\mathbf{x}) = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ T_0 \\ 0 \\ c_0 x_4 \end{bmatrix} \qquad \mathbf{h} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}$$

$$\mathbf{G} = \begin{bmatrix} a_0 & 0 & 0 & 0 \\ a_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \mathbf{n} = \begin{bmatrix} n_1 \\ n_4 \\ n_6 \\ n_8 \end{bmatrix}$$

and

$$\mathbf{f}(\mathbf{x}) = \mathbf{F}\mathbf{x} + \mathbf{f}_1(\mathbf{x})$$

where

$$\mathbf{F} = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & -a_0 & -a_1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & -b_0 & -b_1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & -c_0 & -c_1 \end{bmatrix}$$

and

$$\mathbf{f}_1(\mathbf{x}) = \begin{bmatrix} 0 \\ -A x_4 x_6 \\ 0 \\ A x_2 x_6 \\ 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

The noise statistics, which are normally determined empirically, are chosen to have the following properties, R is a nonzero, positive scalar and $\mathbf{Q}$ is a nonzero, positive definite 4×4 matrix assumed to be diagonal and given by:

$$\mathbf{Q} = \begin{bmatrix} q_{11} & 0 & 0 & 0 \\ 0 & q_{22} & 0 & 0 \\ 0 & 0 & q_{33} & 0 \\ 0 & 0 & 0 & q_{44} \end{bmatrix}$$

where $q_{11} > 0$ $q_{22} > 0$ $q_{33} > 0$ $q_{44} > 0$

The extended Kalman filter equations can now be written as

$$\dot{\hat{\mathbf{x}}} = \mathbf{f}(\hat{\mathbf{x}}) + \mathbf{k}(z - \mathbf{h}^T \hat{\mathbf{x}}) + \mathbf{g}(\hat{\mathbf{x}}) \cdot \sin \omega_0 t$$

where $\hat{\mathbf{x}}$, the output of the Kalman filter, is the estimate of the combined state of the gyroscope and the demodulator. The estimate of the applied torque $\Omega_x(t)$ is given by the state estimate $\hat{x}_7(t)$. $\mathbf{k} = \mathbf{P}\mathbf{h} / R$ is the Kalman gain vector and the error covariance $\mathbf{P}$ is calculated by the equation

$$\dot{\mathbf{P}} = \overline{\mathbf{F}}\mathbf{P} + \mathbf{P}\overline{\mathbf{F}} - \frac{\mathbf{Phh}^T\mathbf{P}}{R} + \mathbf{GQG}^T$$

where

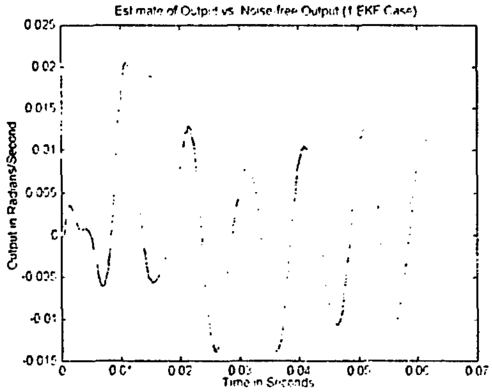
$$\overline{\mathbf{F}} = \mathbf{F} + \mathbf{F}_1$$

and

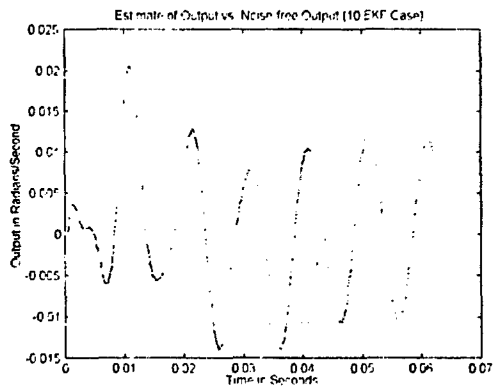
$$\mathbf{F}_1 = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & -A\hat{x}_6 & 0 & -A\hat{x}_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & A\hat{x}_6 & 0 & 0 & 0 & A\hat{x}_2 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

These equations were used to simulate the EKFs used in the simulations.

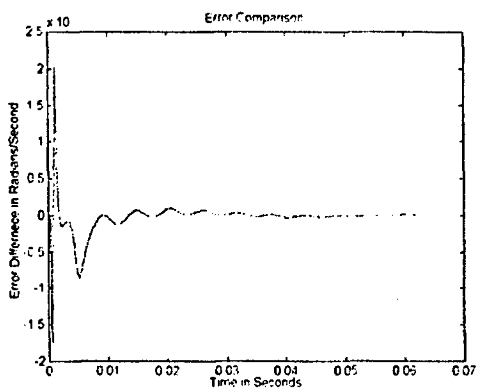
Simulation results: The technique described in this paper of averaging the output measurements from several micro-gyroscopes and processing the average output in a single EKF to estimate the common angular rate applied to each micro-gyroscope was simulated using ten micro-gyroscopes with the micro-gyroscope model described earlier. The applied angular rate input $\Omega_x(t)$ was a sine wave with a maximum amplitude of one-tenth rad/sec and a frequency of one hundred Hertz .A measurement noise with a standard deviation of twenty per cent of the maximum of the steady-state value (.012) of the output signal of the truth model driven by this input was used to corrupt the output of each micro-gyroscope. The output of this simulation was compared to the simulated output of the truth model. The results are shown in the figure below in which the solid line is the noise free output and the dotted line is the estimate. The standard deviation of the time average of the steady state error is $(2.3672)10^{-4}$. This is an improvement of more than ten times over the given measurement noise. With simple averaging, an improvement of $\sqrt{10}$ would be expected.



The technique of developing individual estimates of the applied angular rate using one EKF for each of the ten micro-gyroscopes and averaging the outputs was also simulated and compared to the truth model. These results are shown in the figure below in which the dotted line is the noise-free output and the solid line is the estimate. The standard deviation of the time average of the steady state error is $(2.1058)10^{-4}$.



Finally, the two multiple sensor techniques were compared to each other. The error, compared to the truth model, was generated for each and the difference between these two errors is shown in the figure below.



It is apparent that the two different signal processing methods are very comparable. There seems to be only a slight degradation of the estimate when one EKF is used as opposed to ten EKFs. On the other hand, the amount of computation is considerably reduced.

Conclusions: In this paper a method of improving the accuracy of micro inertial sensors is proposed. This technique uses multiple sensors with advanced signal processing techniques to combine the many signals into a single output. Two such techniques are discussed, the first is very computationally intensive and the second is moderately computationally intensive. In order to be useful, the outputs generated by these techniques should be significantly more accurate than the output of a single sensor or even of the arithmetic average of the outputs of many sensors. Some preliminary simulation results indicate that both techniques improve the sensor accuracy significantly; however, the computational intensity of the first technique increases exponentially with the number of sensors, which precludes it from being used with a very large number of sensors. In the second technique, the computational burden is independent of the number of sensors and if it has comparable accuracy to the first technique then is far preferable. Early comparisons of the two techniques indicates that the accuracies are comparable.

This research is still in a preliminary stage and definitive conclusions are premature; however the early simulations give results that are promising enough to encourage further work in this area.

Distributed Intelligence, Sensing, and Control for Fully Autonomous Agents

(January 1999)

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1. Introduction

Future naval missions at sea or shore will require effective and intelligent utilization of real-time information and sensory data to assess unpredictable situations, identify and track hostile targets, make rapid decisions, and robustly influence, control, and monitor various aspects of the theater of operation. Littoral missions and operations are expected to be highly dynamic and extremely uncertain. Communication interruption and delay are likely, and active deception and jamming are anticipated.

There is an evolving need for a new generation of unmanned aerial vehicles (UAVs) to perform the tasks traditionally attributed to manned aircraft. For example, UAVs such as Global Hawk are rapidly becoming integral part of military surveillance and reconnaissance operations. UAVs are economical, capable of carrying powerful sensors, and complement manned aircraft missions. Other inherent advantages are (a) removal of personnel from hazardous environments; (b) elimination of error-prone repetitive tasks; (c) reduction of cost associated with operational safety and training; (d) expansion of operational envelope; and (e) performing long endurance mission.

Recent advances in high speed computing, information processing, sensors, wireless communications, Internet technologies, and mobile telecommunications have led to emergence of *network-centric systems*. The technology focus is shifting from individual platforms with limited number of agents to multiple platforms with transparent agents. The software and hardware agents are becoming smarter and capable of continuously adapting to changes in the operational environment. The agents can strategize and make decisions to achieve the desired objectives of mission.

At the Office of Naval Research (ONR) we envision airborne intelligent autonomous agents will have the ability to collect, process, fuse, and disseminate real-time information while exploiting and/or denying an enemy similar opportunities. These airborne intelligent autonomous agents are referred to as unmanned combat air vehicles (UCAV). This new capability will enhance the notion of network-centric warfare. It is well understood that network-centric operations can deliver to the US military a distinct edge over the enemy. At the strategic level it provides, not simply raw data but a detailed understanding and situational awareness of the appropriate competitive space. At the tactical level, network-centric warfare allows forces to develop rapid response capability and the ability to command and control the littoral environment in real-time settings.

ONR's approach to the development of the unmanned combat air vehicle systems is based on the premise of decentralized intelligence and cooperative behavior in a distributed fashion. The UCAV's decentralized intelligence resides in its organization of its multiple hosts with wide variety of sensing capabilities and functionality that will enable it to protect mission integrity in hostile, uncertain, and spatially extended environment with no single point failure. This organization will be able to accomplish missions that individual agents cannot. This UCAV system of systems organization is composed of: information systems; sensing systems; control and actuation systems; knowledge discovery, learning, and inference systems; planning and decision-making systems; and communications and networking systems.

To date, autonomous agents have extremely limited intelligence and responsiveness (agility and maneuverability) and lack flexibility. Time latency is a major hindrance in the following areas: adaptation to new operational conditions or component failure , learning new tasks, decision-making, and performing cooperative maneuvers.

This paper outlines ONR's conception of cooperative intelligent autonomous airborne agents with application toward intelligent unmanned combat air vehicles. We will describe how our programs are addressing the architectural issues and design techniques needed for the development of the information, connectivity, dynamic networking, communications, intelligent autonomy, and hybrid and intelligent control elements of the vehicle that comprise the envisioned capabilities.

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

2. Concept of Operation

Figure 1, illustrates a battlefield scenario in which there are several agent teams. There is a ground vehicle team and an air vehicle or UCAV team located in different sectors of the battlefield theater. Two members of the UCAV team are engaged in a strike mission, others in surveillance, and the ground vehicle team is waiting for the opportunity to seize ground control. Though these agent teams may appear to be localized in different sectors with different tasks, they are actually interlocking components commanded by mission control located offshore on a manned control platform. The organization of agents into teams, and the coordination of teams by mission control, transforms a set of agents with localized sensing and actuation capabilities into an organic system that operates over a wide area. Figures 2 and 3, show the hierarchical structure of this organization. Data is shared across layers of the hierarchy and in between peer entities at each layer of the hierarchy.

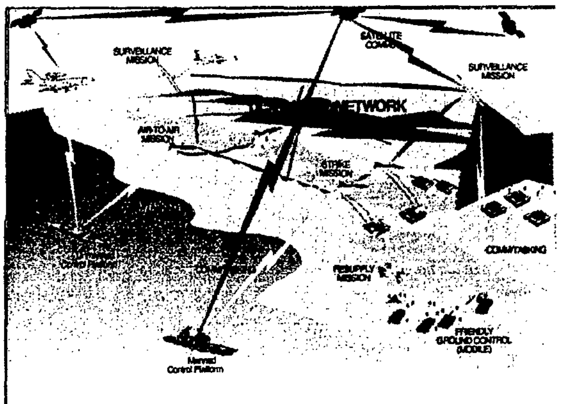


Figure 1. Cooperative UCAV Concept of Operation

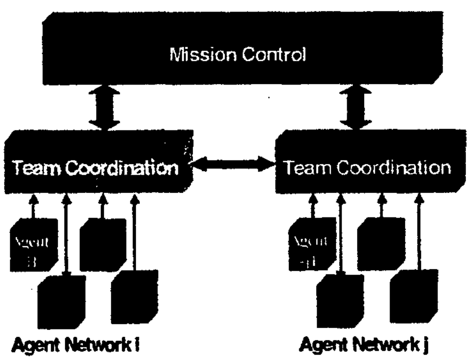


Figure 2: Multi-Agent Organization

The anticipated UCAV missions are close air support, surveillance, reconnaissance, and strike, see figure1.

The principal objective of the vehicles is to enable time-critical over-the-horizon target detection, identification, tracking, and precision engagement where targets could be stationary or mobile and often in clutter environment. To support these missions, the system of UCAVs will be composed of a set of independent and highly maneuverable platforms that individually will support specialized sensors and some will have weapon deployment capability, but in aggregate provide a robust, survivable, and flexible combat capability. A key feature of the UCAVs is their ability to perform autonomous operation for prolonged periods of time, with multiple options for connectivity to higher authority as required for command, control, and mission retasking.

It is highly likely that the UCAVs will be operating in an actively jammed littoral environment where the lines of communication with human command and control centers are cut off and GPS signal nonexistent. Connectivity outages or lack of GPS signal may last for protracted periods of time, from several minutes to a few hours, nevertheless the UCAVs are expected to continue their missions safely and reliably until the communication links and/or GPS signals are reestablished, see figure 4. Therefore, the system of UCAVs must be able to self-organize and adjust to unpredictable events while operating in such harsh environments. Consequently, the vehicles must adhere to the most stringent operational requirements for safety and reliability. Following is a partial list of the expected UCAV operational constraints:

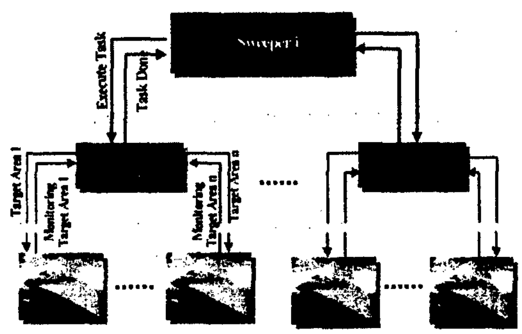


Figure 3. UCAVs Decentralized Hierarchical Architecture

- Operate in jammed environment with limited bandwidth;
- Function with incomplete information;
- Navigate without GPS signal;
- Handle unanticipated events;
- Operate in a fault-tolerant and survivable manner;
- Perform new tasks based on real-time information autonomously;
- Operate beyond line of sight;

- Carry lethal payload;
- Engage in lethal operations such as air-to-air strike and air-to-ground strike for suppression of enemy air defenses;
- Maintain connectivity with remote human-decision centers (naval vessels, aircraft, land-based facilities) from which the decision-maker can interact, intervene, and ultimately override various phases of a mission.

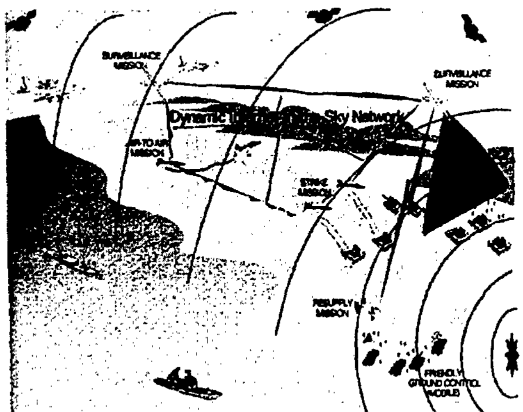


Figure 4. Cooperative UCAVs Connectivity In Jammed Environment

3. Information, Connectivity, Dynamic Networking, and Communications

In the ONR conception, as illustrated in figure 5, connectivity and dynamic networking of UCAVs are based on a decentralized hierarchical organization, where the vehicles have varying domains of responsibility at different levels of the hierarchy. Clusters of UCAVs will operate at low altitude (2K-15K feet) to perform combat missions with a focus on target identification, combat support, and close-in weapons deployment. Mid-altitude clusters (15-50K feet) will execute knowledge acquisition, for example, surveillance and reconnaissance missions such as detecting objects of interest, performing sensor fusion/integration, coordinating low-altitude vehicle deployments, and medium-range weapons support. The high altitude cluster(s) (50K-100K feet) provides the connectivity. At this layer, the cluster(s) has a wide view of the theater and would be positioned to provide maximum communications coverage and will support high-bandwidth robust connectivity to manned command and control elements located over-the-horizon from the littoral/targeted areas.

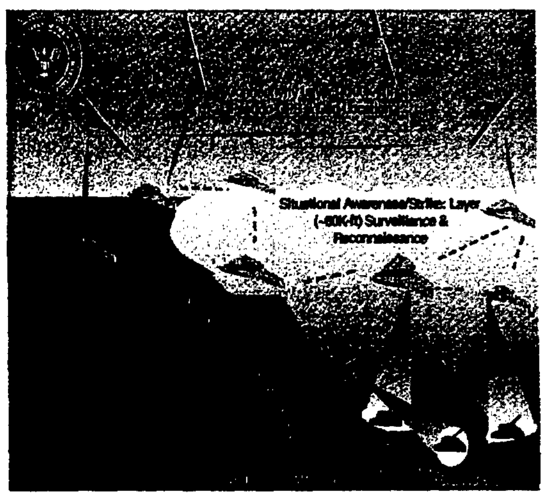
This hierarchical agent organization has architectural features useful for the design of the dynamic network architecture. Higher levels of the hierarchy mostly operate over a greater spatial extent but at slower time-scales. The reason is that the transfer of data over larger spaces usually requires more time, because data transfer requires multiple hops, and in a wireless environment the reliability of a link can degrade rapidly with increasing range. The bandwidth requirements could be derived from the space-time locus of data. Following are some of the key communication requirements for UCAVs:

- **Secure communication** to deny information to hostile forces. This is particularly challenging because the envisioned strength of the UCAVs stem from their ability to share information and perform distributed information processing and fusion;

- **Low-Probability-of-Detection (LPD)/Low-Probability-of-Interception (LPI)/Anti-jamming (AJ)** capability to penetrate deep into hostile territory. Once UCAVs are detected, hostile forces will attempt to disrupt the UCAV's communication system with jamming techniques ranging from broadband noise to optimum fraction-of-the-band jammers;

- **Dynamic resource allocation:** data quality, high throughput, and high performance, for example, low bit error rate, frame error rate, lost data, and delay;

- **Channel and network capacity:** reliability, redundancy, availability, interoperability of communication links to insure a high degree of connectivity, e.g., alternate transmission routes and multihop communications, in hostile environments.



Functional flexibility and interoperability of the UCAVs are essential to the overall mission effectiveness, that is, loss of individual UCAV or malfunction should only result in marginal degradation of the mission. This self-healing/self-preservation characteristic relies on the autonomy which includes redundant functionality, adaptation, and self-reconfiguration, as well as robust connectivity of the aggregate system through:

- Distribution and reallocation of essential functions amongst the vehicles in a given cluster;
- Transfer of UCAVs from one cluster to another.

These capabilities can only be realized through adaptable dynamical communication networks allowing reliable, secure, high throughput connectivity [13,14,15]. These networks can be grouped as:

- Intra-network for secure communications among the vehicles within the local network/line-of-sight;
- Inter-network for secure communications between the vehicles in adjacent networks.

Other significant and challenging issues that our program is addressing are as follows:

(a) Network capacity and resource allocation to perform a specific task or mission. This will depend on the category of the information flow, e.g., command and control, navigation, sensor aggregation, target designation, and network management. The portion of total capacity allocated to each function will vary with mission profile and assigned degree of autonomy.

(b) Adaptive Communications, UCAV's mission diversity and cooperative networking configurations coupled with the vehicle's dynamics and mobility will demand communication infrastructure that is adaptive and dynamic. Therefore, the architecture must accommodate adjustments to changing channels, network configurations, data requirements, and security. Our focus is on developing adaptive connectivity techniques at various levels of the hierarchy, including the physical layer, network layer, data/information layer, and security layer. In contrast to non-adaptive schemes that are designed relative to the worst-case channel conditions, adaptive techniques, take advantage of the time-varying nature of wireless channels. That is, in adaptive techniques the goal is to vary the transmitted power level, symbol rate, coding rate/scheme, configuration size, or any combination of these parameters in order to improve the link performance which includes data rate, latency, and bit error rates (BER), while meeting the system performance specifications. Adaptive modulation has been shown to increase the data rates on flat-fading channels by a factor of five or more. Additional coding can be used to obtain a reduction in transmit power or BER or resistance to jamming. Moreover, the BER in adaptive modulation remains constant independent of channel variations, which greatly improves reliability of the wireless link.

(c) Adaptive Quality-of-Service (QoS), UCAVs will require unique protocols for the QoS. The QoS stands for end-to-end performance metrics for communications link such as bandwidth, latency, and packet dropping probability. Depending on the application, performance metrics defines the minimum requirements needed for good performance. However, for UCAVs, networks are based on dynamic nodes with a dynamic backbone structure. Moreover, network characteristics and applications are mission driven. To secure an acceptable end-to-end performance, the QoS must be adaptive to the network's mission. This adaptation may take the form of variable-rate or multiresolution compression, variable-rate error correction coding, and message prioritization relative to delay constraints, etc.

4. Intelligent Autonomy

Complexity, massive uncertainty, and real-time demands can characterize the operational environment of UCAVs. Crucial elements of intelligence are reasoning, situational awareness, adaptability, learning, decision-making, and contingency planning. Current systems typically lack the ability to learn or to handle unexpected events, either failing, aborting, or referring all such events back to a central human controller. Therefore. UCAVs require a combination of new technologies for sensing, control, learning, communications, and high-level decision making.

Hierarchical structuring is key to the overall design of autonomous intelligent agents. The replication of human optimal decision making process for systems in such UCAV environment, is intractable by the complexity of the task environment. In general, the only way to manage intractability has been to provide a hierarchical organization for complex activities. Although it can yield suboptimal policies, top-down hierarchical control often reduces the complexity of the decision making from exponential to linear in the size of the problem. For example, hierarchical task network planners can generate solutions containing tens of thousands of steps, whereas "flat" planners can manage only tens of steps. The goal is to achieve similar improvements in the ability of the systems to construct complex plans including contingency planning and handling unpredictable events in environments, such as UCAV environment, that are characterized by massive uncertainty.

In both Control Theory and Artificial Intelligence (AI), there is now a consensus that probabilistic and decision-theoretic methods provide a rigorous foundation for optimal decision making in environments with partial and uncertain sensory data and uncertain dynamics. For example, stochastic optimal control relates directly to AI work on rational agent design. In control theory, online and offline design of control laws is used to address continuous-domain events in environments; in AI, online decision making is used to handle environments with large numbers of discrete variables. ONR's approach is to merge AI and Control-theoretic approaches by developing technology tools for handling the representational and inferential complexity inherent in large, hybrid environments such as UCAV's.

In rational agent design and stochastic control theory, a key concept is known as the belief state: the current joint probability distribution over states of the environment, conditioned on all prior observations [1,2]. With incomplete and noisy sensors, optimal decisions must be computed from the current belief states. In the case of hybrid domains with both discrete and continuous variables, the belief state if explicitly represented grows exponentially with the number of variables. Avoiding this exponential growth is essential. Probabilistic networks (PN) also known as Bayesian networks produce structured representations for complex environments and they are now in wide use for static tasks such as diagnosis, help functions in software products, and situation assessment. Dynamic probabilistic networks (DPNs) extend PNs by including multiple connected copies (called time slices) of a static PN, thereby enabling the modeling of stochastic temporal processes [3]. DPNs serve a number of purposes, see figure 6:

- ***Monitoring:*** This requires computing the belief state incrementally as new sensor data arrives over time and it easily handles multiple noisy sensors, sensor failure, etc.

- ***Prediction:*** This requires computing a probability distribution over possible future evolutions of the observed system, and is done by adding slices into the future (this is called filtering).

- ***Hindsight:*** This requires computing the posterior distribution at any past time given all evidence up to the present time.

- ***Decision Making:*** By combining prediction with decision nodes representing possible actions by the system itself, one can achieve approximately optimal decision-making with a limited horizon.

The DPNs are expected to model processes that operate at a wide range of time scales. For example, the UCAV must be able to reason about the weather @ 0.01Hz and the behavior of other UCAVs @ 100Hz or manned aircraft @ 10Hz. There is a close relationship between DPNs and Nonlinear Filtering Theory including Kalman Filtering concepts which are widely used in modern Guidance, Navigation, and Control of dynamic vehicles.

On the intelligent agent architecture the issues of prime importance are: real-time decision-making, adaptation, learning, and hierarchical decomposition. Real-time control is handled by metareasoning and by the integration of multiple execution architectures ranging from compiled control laws to online planning. Adaptation and learning must take place at all levels of the hierarchy, since one can not assume that the environment and correct system structure are known at the outset. This includes learning the environment from sensory inputs, direct learning of control laws in supervised and unsupervised setting, and verification for learning systems – that is proving the resulting systems configuration and the strategy will be effective. Figure 7 illustrates the architecture of an intelligent autonomous agent. Such agents are designed to recognize the inadequacy of their information in an unfamiliar situation and respond by mining available data sources to create new information.

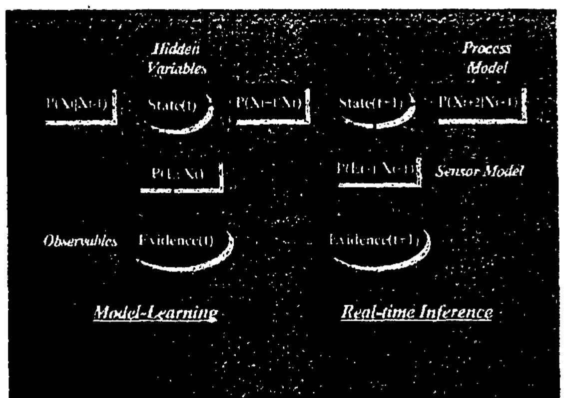


Figure 6. DPN Structure

For example, if a UCAV flying over a sector detects and geolocates a static target that it cannot recognize, it may attempt to augment its information by searching for pre-existing maps that show an object in the same location or ATR logs of other UCAVs' that have passed over the sector, see figure 8. This implies that the information library (see figure 7) should be a shared resource, populated on the basis of the collective experience of the agents, and accessible to all. This is analogous to the way libraries are managed in large institutions. This concept of a heterogeneous knowledge base is a key feature of cooperative agents such as UCAVs. The space-time locus of the knowledge base should track the space time locus of the agents and their data needs.

Real-time decision-making is a crucial capability for UCAVs. However, it is essential to make the following distinctions among decision situations:

- ***Low-level open and/or closed-loop control:*** Control over actuators during maneuvers, e.g., landing on a moving deck, requires very fast execution. At this level of control, rapid execution is possible because only a few aspects of the environment are relevant and uncertainty is constrained.

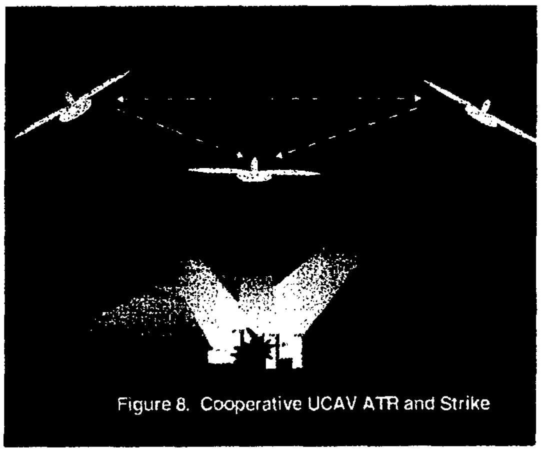


Figure 8. Cooperative UCAV ATR and Strike

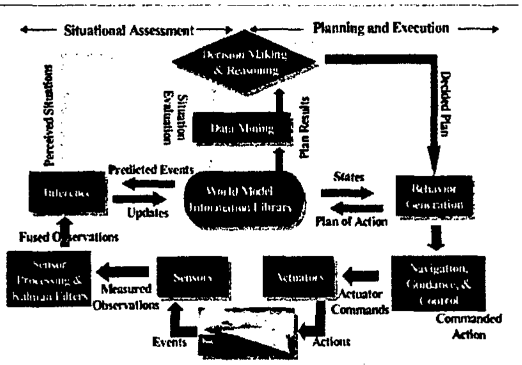


Figure 7. Intelligent Agent Architecture

- ***High-level precomputed decision strategies:*** Some high-level decisions must be made very rapidly, e.g., what maneuvers to execute when faced with multiple incoming threats. These decisions, which deal with a large number of variables and considerable uncertainty, are intrinsically complex and must therefore be precomputed offline. Reinforcement learning, dynamic programming, and genetic/evolutionary learning methods can do this [9,11].

- ***High-level decisions in combinations of different circumstances:*** It is inevitable that a UCAV will face some combinations of circumstances that have not been anticipated during earlier offline learning and precomputation. For example, a new mission that requires a new route may require some deliberation before the UCAV can decide which route to start flying. Such decisions need not be made instantaneously; on the other hand, it is simply unacceptable for a UCAV to deliberate for ten minutes. The amount of deliberation must be appropriate to the urgency of the situation and to the value of deliberation for further improvements in decision quality. This can be handled using *rational metareasoning* and composition of *anytime algorithms*.

Rational metareasoning means deciding optimally or nearly optimally which computations to carry out. This can be done by comparing the estimated benefit in terms of improved decision quality with the estimated cost in terms of time (and the implied deterioration of the situation). For example, if the UCAV has decide to return to base because of a serious fuel leak, it is pointless to deliberate further about the location of possibly interesting naval operations in the battle arena. On the other hand, at the beginning of the mission it might be worth spending a minute or two plotting an efficient, safe route and gathering additional intelligence.

Rational metareasoning, along with various other iterative algorithms for generating successive approximations, results in *anytime algorithms* whose decision quality increases monotonically with the amount of computation allocated. UCAVs are expected to contain many such algorithms, e.g., for visual scene interpretation, course computation, weather prediction, cooperative planning with other UCAVs. Thus, it is crucial to be able to allocate computational resources optimally among a large collection of anytime processes.

The principal representation tools for environment models are PNs and DPNs. The PN learning is a local update process using information obtained directly from the inference algorithm. Thus, a simple local update process allows the PN to adapt itself optimally to the environment. This form of learning can be performed offline or online. The DPN learning is similar to PN but it is a dynamic learning process, e.g., the sensor and state evolution models are replicated across time steps.

Reinforcement learning (RL) is the process of learning based on rewards, e.g., short-term payoff information from the environment (useful in UCAV tactics maneuvers). Partially observable environments, which constitute the vast majority of UCAV's missions, require optimal decision-making on the basis of the current belief state. Solving partially observable decision problems is NP-hard, RL can help to reduce the complexity, e.g., RL focuses on the states arising in the UCAV's actual flight experience. The approach is based on hierarchical reinforcement learning known as hierarchical abstract machine (HAMs). A HAM is a partial specification of behavior that can range from very general, e.g., "fly around over a region of interest, identify moving objects, then come back and land on one of the following ships", to very specific, e.g., "execute the following flight path and maneuvers". Thus, HAMs can be used to place constraints on the behavior of UCAVs, such that the UCAV will execute the optimal strategy that is consistent with the planned mission specifications.

5. Hybrid and Intelligent Control Architectures

Intelligent autonomous systems such as UCAVs are viewed as hybrid multi-agents systems that sense and manipulate their environment by gathering multi-modal sensor data, and compressing and representing it in symbolic form at various level of granularity [6]. The representations are then used by the vehicles to reason and learn about how to optimally interact with the environment. In real world, environments are complex, spatially extended, dynamic, stochastic, and largely unknown. Intelligent systems must also accommodate massive sensory and motor uncertainty and must act in real-time. The hybrid dynamics arise from the interactions between continuous and discrete events and coordination protocols [5,7,8,10,12]. At the continuous level, each agent chooses its own optimal strategy, while discrete coordination is used to resolve conflicts.

The new paradigm that ONR is pursuing for the UCAVs is known as the hybrid distributed hierarchical perception and control. This paradigm is composed of the following key elements:

- Intelligent hierarchical control architectures for autonomous agents that share a single environment;
- Decentralized information and control to maximize a successful and fault-tolerant mission through rapid and dynamic reconfiguration of the inter-agent coordination protocols;
- Perception Systems: (a) hierarchical aggregation of decision and control; (b) wide area situational awareness; and (c) low-level perception.

For safety purposes, the UCAVs are expected to have multiple levels of autonomy and controllability, ranging from teleoperation, to interactive, to fully autonomous meaning that autonomy with intelligence to enable the vehicle to respond rapidly to dynamically changing environments.

It is expected that in a large spatially distributed theater of operations, the sensory systems of individual agents are able to obtain localized and noisy/incomplete information, though mission objectives demand that the agents act quickly, decisively, and cooperatively to optimize mission objectives. One approach is to decompose the process that maps sensory information to control actions in two steps:

- First step is mapping of information about the unpredictable, partially modeled, internal and external environment of the agent into a top-level control decision, which is accomplished through soft computing techniques. These techniques are characterized as goal oriented planning, perceptual reasoning, optimal decision making in stochastic control, and pattern recognition in neural networks;
- Second step is the process that maps the top level control decision to the sequence of control and coordination actions that cascade through the multi-agent system, and ultimately result in the activation of various agent effectors.

For the development of the intelligent control architecture, there is a continuum of design choices for systems decomposition, ranging from strict hierarchical control to a fully distributed multi-agent system. We envision an architecture that allows different choices that are appropriate at different levels of abstraction:

- Continuous domain, for low-level control systems, is concerned with safety and smooth execution;
- Discrete domain, for symbolic and discrete strategic levels, is concerned with optimization and planning for high-level goals;
- Interface and organization of hybrid systems to attain emergent behavior of the collective system of agents for the usage of scarce resources by many agents operating with varying degree of autonomy.

The conceptual underpinning for intelligent, multi-agent systems is the ability to verify that the sensory-motor hierarchies perform as expected. The UCAV will need to have multiple modes of operation, including takeoff, land, track, etc. It is important for the vehicle to verify the modes, e.g., the vehicle should self check the control algorithms that switch between the modes based on high level commands and vision data to prevent the vehicle to enter unstable or unsafe states. In the event of failure or damage, the UCAV must maintain the integrity of the vehicle and safety with possible gradual degradation in the performance of the system.

On the multi-layered hierarchical architecture the higher layers are typically modeled by discrete-event systems, which plan and reason under uncertainty, and assume strategic decisions in coordination with other agents. The lower-layers involve continuous dynamics and perform path planning and regulation tasks. Figure 9 illustrates such a multi-layer hierarchical organization of diagnostics and control layers required for fault management of autonomous vehicles. The hierarchy consists of multiple levels where each level is functionally autonomous. The information flows both ways between the layers while the control commands are passed one way from higher layers to the lower layers. The lower levels of the hierarchy exercise localized control and operate at higher speeds. As one moves up the hierarchy, the domain of influence becomes more global and the decision time cycles grow longer. At each level of the hierarchy, an appropriate world-view can be developed and converted into a model for inference and decision, for example:

- **Vehicle Layer:** Represents UCAV airframe, engines, actuators, control effectors, vision and other sensors, etc. This level provides accurate measurements and assures fast and reliable response of the UCAV to the commands generated by other levels.

- **Regulation Layer:** (a) Adaptive Reconfigurable Flight Control Sub-layer: performs on-line failure detection and identification, control reconfiguration, and signal processing; (b) Autonomous Intelligent Flight Control System Sub-layer: provides trajectory optimization and tracking, and set-point control.

- **Tactical Layer:** This layer executes the plan generated by the Strategic Planning layer. Speed is critical at this level. The main objective of the level is to coordinate the activities of various UCAV missions and dynamically execute tasks such as target assignment, flight mode switching, and trajectory planning.

- **Strategic Layer:** This layer performs autonomous decision making, learning, and verification. It performs threat detection and assessment, and fault management. At this level the supervisor essentially generates long term plans that will result in a successful mission and performs some level of inter-agent coordination. Tasks performed at this layer are computationally intensive.

- **Mission Layer:** This is a mission supervisory layer (such as reconnaissance and surveillance, strike, resupply) and provides human-machine interaction. The supervisor at this level coordinates its mission with other agents in the network, allocates resources, performs tasks at a discrete level such as route planning, and resource allocation.

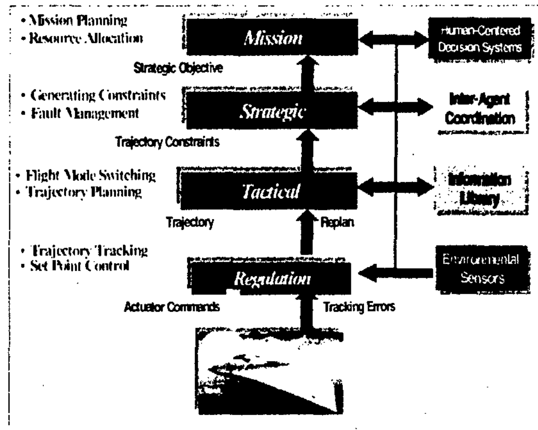


Figure 9. Multi-Layer Hierarchical Control Architecture

Intelligent control can be broadly defined as a set of strategies combined in a suitable manner to achieve the desired control objectives in the presence of large uncertainties, fast variations in the system dynamics, and constraints. The emphasis is on large uncertainties and fast variations, which is the main feature of intelligent control systems in comparison with, for instance, robust or adaptive controllers. Intelligent controllers can be designed using Multiple Models, Switching, & Tuning (MMST) technique [4]. The MMST framework is closely related to the intelligent decision-making framework encountered in biological systems. A biological system continuously learns by building different models of its environment and storing this information in the memory. In any new situation, it compares the current information with that stored in memory, based on the model that is closest in some sense to that of the current environment, takes appropriate actions. The MMST concept, shown in figure 10, has been developed using similar ideas. In the figure, models 1 thru n are different operational/event models (observers), while controllers 1 thru n are the corresponding decision-making mechanisms. In the context of intelligent reconfigurable control, the observers are built using linear or nonlinear models associated with different modes of operation (normal mode and failure modes of the system and its components). For each of these models there is a corresponding adaptive reconfigurable controller. The mixing and switching mechanism compares the information obtained from the observers with available measurements and, based on the model that is closest in some sense to the current operating regime of the plant, chooses the corresponding controller.

One of the main features of the MMST methodology is its flexibility. Both observers and controllers can be either fixed or adaptive, and linear or nonlinear. The above structure can be used for identification, estimation, and prediction. It can also be used to estimate the current environment and available resources, and make appropriate decisions. The same structure can be used at higher hierarchical levels where, based on inference methodologies and decision making algorithms, appropriate decisions related to the overall system can be made. Besides its flexibility, the other important feature of the MMST methodology is that in many cases the stability, robustness, and performance of the systems containing MMST observers and controllers can be explicitly evaluated.

6. Summary

We described the envisioned architectures and technology capabilities needed to develop a robust, adaptive, and dynamic communications, information, decision, and control infrastructure supporting a class of cooperative and distributive intelligent autonomous air vehicles or UCAVs. This infrastructure will be used to organize the mobile agents into dynamic teams supporting complex missions such as surveillance, target detection and tracking, and coordinated attack. The dynamic network provides connectivity for real-time situational awareness in the littoral environment and exchange of real-time information between agents. The connectivity requirements of the underlying mission include real and non-real time data transfer as well as data retrieval from fixed and mobile databases. This communications infrastructure will provide a unique and powerful mechanism for the Navy to carry out complex missions with minimal risk and vulnerability.

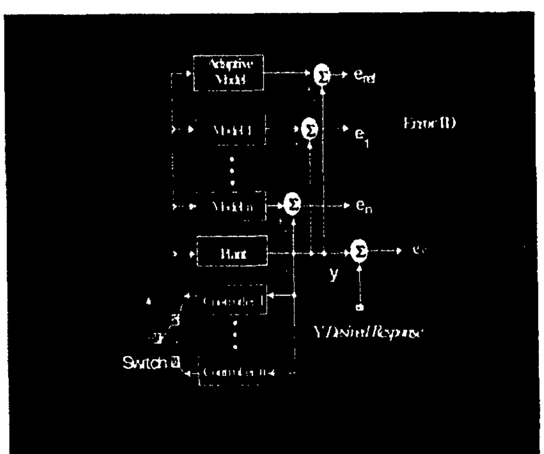


Figure 10. Multiple Model Switching and Tuning

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Command and Control System of Unmanned Surface Drones for Sea Mine Disposal

The Automation of Minesweeping Operations
by means of the
Command and Control System (C^2 System) for the
Remote-Controlled Mine Countermeasures System TROIKA

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1. Summary

The following presentation gives an overview about the concept and the capabilities of the new command and control system for remote controlled unmanned surface drones which will be used for disposal of seamines. The presentations shows that a reasonable automation of minesweeping operations with unmanned drones under heterogeneous operating conditions is possible and will improve the sweeping performance significantly.

2. Mission of the Mine Counter Measure (MCM) System TROIKA

- *What is the purpose and the basic configuration of the minesweeping system?*

The TROIKA minesweeping system is used by the German Navy to dispose sea mines (picture 1).

The TROIKA system consists of a manned guidance control platform (GCP) from which of up to three unmanned boats (drones) can be remotely controlled in manual mode. These drones generate magnetic and acoustic signatures which initiate sea mines at a safe distance from the guidance control platform and thus clear the sea area of mines. The drones are designed to survive the mine detonations and remain operable.

The task of TROIKA comprises the transit of the force (guidance control platform and drones) to and from the sea area and the very minesweeping operations themselves in the operating area.

3. The Need for Automation of Today's MCM System TROIKA

- *Why is it necessary to automate minesweeping by the TROIKA system?*

During minesweeping the drones must operate directly in the minefield to initiate the mines. Due to the resulting hazard they must be unmanned during such operations.

The drones are controlled and monitored remotely from the guidance control platform which is located outside the minefield.

At present, remote control is performed manually, i.e. the control commands for the drone are entered by the operator on the guidance control platform, from where they are transmitted to the drone by radio and executed. The drone position is determined by the guidance control platform radar. The operation is not automated.

Such manual remote control has the following disadvantages (pictures 2 and 3):

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

- **High manpower requirements**

A control operator is permanently required for each drone because each drone is controlled manually. In addition, one person is required for monitoring the entire operation and the sea area.

- **High stress load for the operators**

The control operators on the guidance control platform can observe and assess the surface situation (drone position and movements, other traffic) only by means of the radar image. This requires enormous concentration and is very monotonous and is thus an extremely stressy job for the operators.

- **Prolonged stress load for the operators**

The sweeping areas are very large; they must be run over by the drones repeatedly and the drones are very slow. Therefore, a minesweeping operation and thus the stress for the operator is very lengthy (up to several days).

- **Varying sweeping performance and success**

The sweeping performance and success depend on how exactly and completely the given sweeping tracks can be covered by the drones. With manual control this is dependent on the operator's attention, current capability and level of training and therefore strongly varies. The limited observation means (only radar image) make the correct reaction by the operator difficult and reduce the sweeping performance.

- **No permanently evaluation of sweeping progress and no documentation**

The sweeping progress is not permanently documented and evaluated.

All this shows that manual remote control of the drones has considerable disadvantages.

4. Requirements for the Command and Control Capability of the Future Mine Countermeasures System TROIKA

- *What are the requirements for a future minesweeping system with respect to operational command and control?*

The TROIKA minesweeping system has proven to be an efficient means of sea mine disposal in practice, which is underlined by its successful employment in the Arabian Gulf. Germany is currently upgrading its mine countermeasures capabilities. One of the measures taken is to improve the drone control, in order to eliminate the disadvantages of remote control described above and to increase the efficiency of sea mine disposal.

The command and control capability of the new TROIKA system will have to meet the following requirements (picture 4):

1. The operator workload and stress will have to be greatly reduced.
2. The sweeping performance and success will have to be improved.
3. The command and control system shall not affect the planning and conduct of operations.
4. Manual control of one or several drones must always be possible.
5. Changes to the planning and conduct of the operation must always be possible, even during the operation.
6. Nautical safety shall be improved.
7. The current MCM situation and the sweeping success/situation shall be updated and documented permanently.
8. Data exchange (MCM situation, planning data) with other MCM units must be possible.

The operational conditions in times of crisis and peace shall be taken into consideration. Economic solutions shall be realized.

An analysis of the requirements shows that all requirements can only be met with different types of solutions (picture 5). Requirements for a reduced operator workload and stress along with an increased sweeping performance call for an automated high-precision drone control and navigation. On the other hand, manual control without any automation of the drone movement must be possible at any time. And finally, drone control must be flexible enough to permit all the different phases of the operation to be conducted without limitations. If one takes a look at the individual phases of a minesweeping operation, it becomes obvious that for some phases drone control is clearly defined and can thus be automated, while other phases require a situation-oriented definition and can only be semi-automated.

In order to meet all these requirements to the optimum extent, a command and control means will have to permit operating the drones at various levels of automation, from fully automatic mode to manual mode.

5. Modes of Operation and Levels of Automation

- *How can the requirements for an improved command and control capability by automation be realized and what will such automation have to look like?*

In order to realize the various requirements, different modes of operation with different levels of automation were defined for drone control (picture 6).

The drones are always controlled in one of the two control modes:
(A) Drone unmanned in remote control
(B) Drone manned in local control

<u>(A) Drone Unmanned in Remote Control</u>
In this control mode the drones are unmanned and remotely controlled from the guidance control platform. This can be done in the following modes of operation:
(A1) fully automatic control
(A2) semi-automatic control
(A3) manual control

The individual modes of operation can be freely selected and changed. At the same time, different modes of operation can be performed by several drones.

<u>*(A1) Remote Control - Fully Automatic*</u>
In this mode a drone or a drone formation is controlled fully automatically. As a prerequisite for using this mode, the entire operation must be completely defined beforehand and the drones must be in a defined status (position and equipment status).
When using this mode, one or several drones can always be switched to another mode of operation.

The mode "Remote Control - Fully Automatic" can be used in two conditions:
(A1-1) Remote Control - Fully Automatic Transit
In this condition the drones automatically follow a reference vessel (the guidance control platform or a drone). It is possible to select whether they follow the track of the reference vessel at a defined distance or whether they synchronously perform the course and speed changes of the reference vessel.
This condition is used when the drones have to be deployed over long distances.

(A1-2) Remote Control - Fully Automatic Minesweeping
In this condition the drones move in a sweeping area and follow a defined sequence which determines:
- the position, number and geometry of the minesweeping tracks to be covered
- the sequence of drone runs
- the type of turns at the end of the track
- the frequency of the track runs
- the drone status during the track runs (type of signature generation, speed, distances)

This condition is used to sweep a sea area.

<u>*(A2) Remote Control - Semi-Automatic*</u>
In this mode the drones are controlled semi-automatically. The system completely controls the compliance with certain inputs (e.g. course, track, speed...). These must be entered manually, they cannot be defined in advance and they are carried out immediately. This mode can be selected in any drone position and situation.

This mode can be used in three conditions:
(A2-1) Remote Control - Supported Mode - Course Following
Selected course and speed of the drone are controlled automatically.

(A2-2) Remote Control - Supported Mode - Track Following
The drone is automatically kept on a defined track with a defined speed.

(A2-3) Remote Control - Supported Mode - Waiting Circle
The drone is automatically kept on a defined circle with a defined speed. Thus, the drones can be "parked" in a way at a fixed position.

<u>*(A3) Remote Control - Manual*</u>
In this mode the drone is not controlled by the C^2 system. The operator enters the control commands manually on the guidance control platform and the C^2 system transmits these commands to the drone. This mode corresponds to the capabilities of today's remote control system of the TROIKA.

<u>(B) Drone Unmanned in Local Control</u>
In this control mode the drones are manned and controlled by the C^2 system on the drone. The following modes of operation can be selected:

(B1) semi-automatic control
(B2) manual control

These modes are structured analogously to those of the remote control mode. The only difference is that the control commands are not entered on the guidance control platform, but directly on the drone.

6. Employment of the Different Levels of Automation During Minesweeping

- *How can the different modes of operation and levels of automation be employed?*

The different drone control modes can be used flexibly without any limitations if the individual prerequisites are fulfilled. The employment of the different modes of operation and hence the different levels of automation shall be explained for a typical minesweeping operation (picture 7).

A minesweeping operation basically consists of the following phases:

- preparation of the operation
- transit
- minesweeping
- completion of the operation

Transit and minesweeping can be performed repeatedly.

6.1 Preparation of the Operation

In addition to the usual readying for operation of the vessels, a radio link must be established between the guidance control platform and the drones, in order be able to monitor the drone status automatically from the guidance control platform.

Then, relevant operational parameters and plans must be defined, e.g. how a sea area shall be swept.

If the minesweeping phase is to be performed in fully automatic mode, a plan for the operation must be prepared in advance. This planning can be very extensive since very many parameters must be defined. In order to reduce this effort, the C² system offers support tools like automatic generation of track geometries, predefined sweep plans etc. The input of a plan for the operation is also possible via data exchange with different data carrier types. This allows a preparation of these plans on other vessels or on landbase station.

6.2 Transit

Transit is the deployment of the minesweeping force to or its return from the operating area (picture 8). During transit, the force usually covers large distances which takes a relatively long time. Therefore, fully automatic drone control, i.e. the drones automatically follow the manually controlled guidance control platform, appears reasonable.

This type of transit is possible with the "Automatic Transit" mode of operation. Since at the beginning of the transit the drones can be in any status (positions, equipment settings), while an automatic transit requires defined initial settings, this transfer to the defined initial status should reasonably be performed semi-automatically or manually. A fully automatic solution would be technically feasible, but not advisable for economic reasons due to the required efforts. In addition, the benefits would be limited because this transfer is performed only for a short time and not very often.

6.3 Minesweeping

During the minesweeping operation itself the drones shall repeatedly run over tracks in a sweeping area in certain modes (picture 9). Normally, this takes quite some time and requires high-precision navigation. Therefore, this process should be fully automated. The prerequisite for fully automatic drone control is that the drones are in defined positions. As during transit, the drones must be transferred from their random positions to the defined starting positions. For a cost-effective realisation of this automatic mode, this is done semi-automatically or by manual control.

6.4 Avoidance of collisions

During the entire operation, incidents (equipment failures, collision hazards etc.) may occur. Theoretically, an automatic reaction would be technically feasible in many cases; however, due to the unlimited variety of possible failures and in order not to relieve the operator of his responsibility, the automatic execution of a reaction (e.g. automatic course change without confirmation by the operator) was waived.

In order to increase the nautical safety, the C² system performs automatic sea surveillance. Collision hazards for the drones or the guidance control platform with moving surface targets are automatically recognized, evasive maneuvers (e.g. course change, speed change) are recommended, and - if confirmed or adjusted by the operator - performed automatically. The drone in question is then switched to the semi-automatic condition "supported mode - course following".

7. System Description

- *How does the automation effect the system design of the C² system?*

To realise high-level, flexible and safety automation of drone control the C²-System has the following main features (picture 10):

The guidance control platform is equipped with two operating consoles with two screens each, which permit comprehensive information display. One console controls and monitors all drones (max. 4), the other console controls, plans and evaluates the overall operation. A flexible and adaptable human machnine interface (HMI) guarantees easy handling of the C² system in each opertional situation.

The drones are fitted with an input device with a display to permit manned control from the drone.

One essential component is a reliable data link between the drone and the guidance control platform. This reliable data link is very important since the drones participate in sea traffic in unmanned mode and must therefore be controllable at any time. Reliability is ensured by several measures, e.g. time division multiple access (TDMA), error correction and diversity operatoin.

8. Realization and Lessons Learned

The command and control system for the control of surface drones has been under development since 1996 in cooperation with the Netherlands (picture 11). Development will be completed in mid-1999 and initial experience can be obtained under real operating conditions. From the year 2000, the new system will enter into service in Germany with the HL 352 class boats (upgrade project HL 343). The same system will also be installed on the Alkmaar class boats of the Royal Netherlands Navy and the use is planned for the German new mine hunting equipment (MJ 2000) which used remotely controlled drones to tow modern sonars.

Simulations with the system and with operators have shown that the operator stress can be significantly reduced with such an automated system.

9. Conclusion

With the new command and control system for the mine countermeasures system TROIKA the German Navy takes its first step towards automated minesweeping.

The design of this system is an example of how automation can be utilized for real operating conditions with heterogeneous and unpredictable situations.

The new C² system has the following advantages:

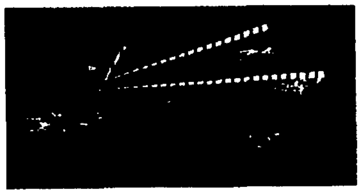
- The automation of drone control reduces the operating effort and the operator stress in such a way that with a manpower reduction from 4 to 2 operators the number of controllable drones can be increased from 3 to 4.
- High-precision navigation in connection with automatic operation analysis and documentation improve the sweeping performance and success.
- Automatic sea surveillance increases nautical safety.
- The use of different levels of automation provides for a flexible, situation-oriented employment and permits an economic realization of the system.

This design of the new C² system offers a maximum degree of automation, flexibility and cost-effectiveness for an effective minesweeping.

C²-System TROIKA

Current TROIKA

- Mission of TROIKA:
  - ***Disposal of sea mines without endangering of personal***
- TROIKA unit covers:
  - ***one manned Guidance Control Platform (GCP)***
  - ***three unmanned <u>manual</u> remotely controlled drones***
- Principle of TROIKA:
  - ***Unmanned drones generate magnetic and acoustic signatures which initiate mines***



Picture 1

C²-System TROIKA

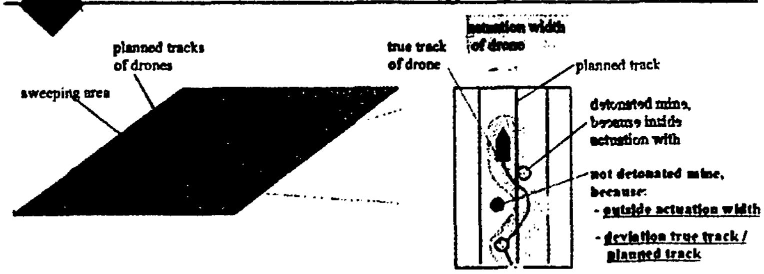
Disadvantages of manual control (I)

- **High manpower requirements**
  - each drones requires one operator and one supervisor
- **High stress load for the operator**
  - observation drones only by radar image
- **Prolonged stress load for the operator**
  - large sweeping areas and large transits / slow drones
- **Varying sweeping performance and success**
  - sweeping performance depends on operator´s attention, current capabilities and level of training
- **No permanently evaluation and documentation**

Picture 2

C²-System TROIKA

Disadvantages of manual control (II)



- **Observation errors (radar image !)**
- **Insufficent manual reaction of operator**

→ **Deviations between planned and true track of drones** →

- **Insufficent sweeping success**
- **Reduced sweeping performance**

Picture 3

C^2-System TROIKA — *Requirements on a new Command and Control System*

- Reduction of operator workload
- Improvement of sweeping performance / success
- No restriction by planning / execution of operations
- Possiblility of manual control at any time
- Possiblitity to change operation planning at any time
- Improvement of nautical safety
- Permanently evaluation and documentation of sweeping situation / success
- Data exchange with other units / landbase

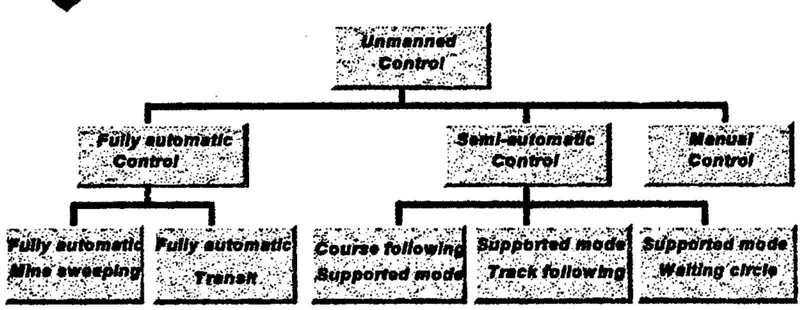
Picture 4

C^2-System TROIKA — *Solutions*

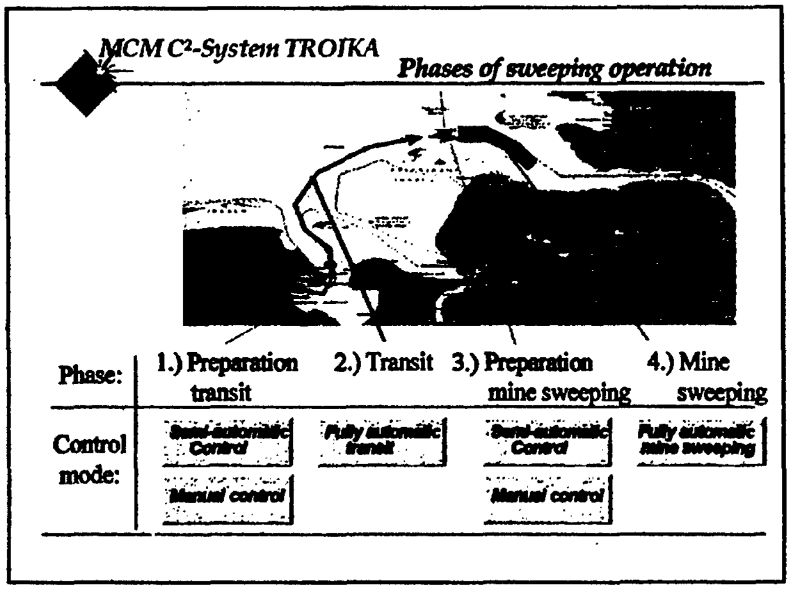
Requirements	Solutions
• Reduction operator workload • Improvement sweeping performance • Permanently evaluation and documentation of	• Fully automation of complete minesweeping operation • Effective and user-friendly operation system
No restriction by planning/execution • Possiblility of manual control at any time • Possiblitity to change operation planning/execution	• Flexibel automation • Different levels of automation for each drone
• Improvement of nautical safety	• Automatic collision detection and support of evasive actions • Reliable data link

Picture 5

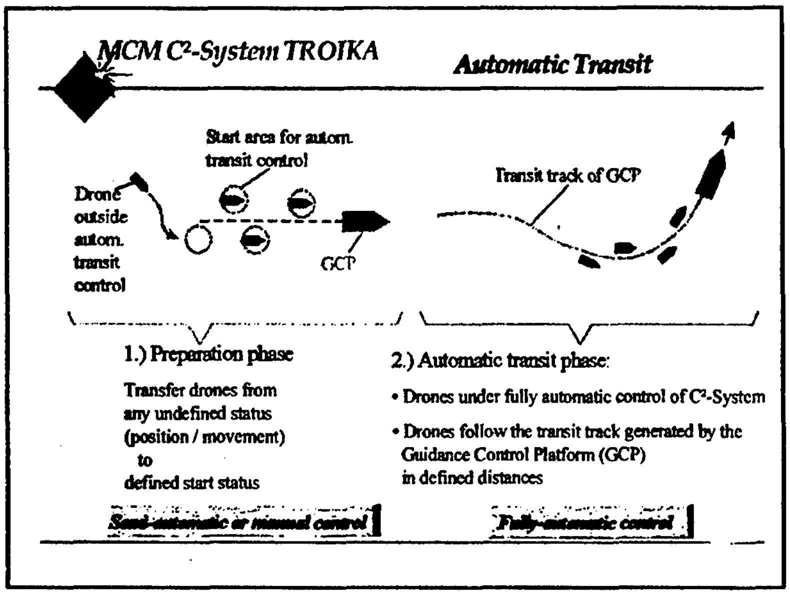
C^2-System TROIKA — *Different levels of automation*



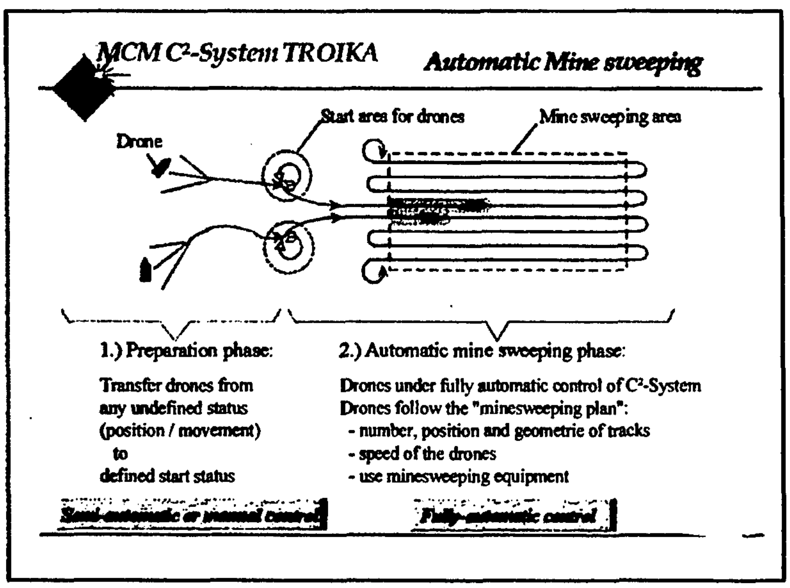
Picture 6



Picture 7



Picture 8

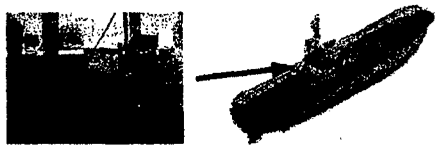


Picture 9

C²-System TROIKA — ***Components of new C²-System***

- Guidance Control Platform
  - two identical consols (operator and supervisor) each console two screens
  - interfaces to navigation sensors
  - main computer
  - data link unit

- Drones
  - input device with display (for manual control on drone)
  - interfaces to navigation sensors
  - interfaces to drone control
  - data link unit

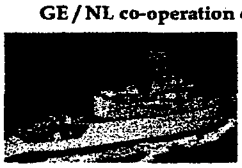


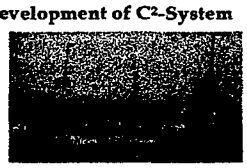
Picture10

C²-System TROIKA — ***Use of new C²-System***

Use of new the Command and Control System
for remote controlled drones

GE / NL co-operation development of C²-System





- NL upgrade project of Alkmaar class
- In service planned 2002

- GE upgrade project of HL 343
- In service planned 2000

- GE development project of new mine hunting equipment (MJ 2000)
- In service planned 2006

Picture11

C²-System TROIKA — ***Conclusion***

- **First step towards automated minesweeping**
- **Automation and high-precision navigation improves sweeping performance / success and reduces operator stress**
- **Flexible automation allows optimal use under any real operating conditions**
- **Automatic sea surveillance increases nautical safety**

Picture12

Test and Evaluation of the Man-Machine Interface Between the Apache Longbow™ and an Unmanned Aerial Vehicle

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ABSTRACT

The Boeing Company is studying a concept that involves teaming a manned rotorcraft, the Apache Longbow™, with a unmanned air vehicle (UAV). During 1997 Boeing developed a preliminary man-machine interface between the Apache Longbow and an unmanned air vehicle. An early assessment of the man-machine interface in a virtual simulation environment was conducted. The study concentrated on the effects of crew workload during manned-unmanned teaming operations and acceptability of the design in terms of presentation of the data, functionality, and utility. A limited assessment of operational measures of effectiveness was also conducted. Subject pilots were satisfied with the man-machine interface, did not experience task overload and were able to perform UAV control tasks. Subjects did experience some difficulty with target acquisition and tracking, however. Initial data suggests that the potential exists to detect targets beyond the organic sensor range of current attack/reconnaissance rotorcraft without being exposed to threat detection.

INTRODUCTION

The ability to link a UAV to a manned reconnaissance/attack rotorcraft has the potential of substantially improving mission effectiveness during reconnaissance and attack operations. UAV electro-optical and FLIR sensors provide for surveillance, targeting and battle damage assessment functions. Extended sensor range offered by the UAV remote sensor capability may provide increased situational awareness and reaction time, which has the potential to increase the lethality, survivability, and mission effectiveness of attack/reconnaissance teams. A major concern is the level of crew interaction required and the workload placed on the crew for effective manned-unmanned teaming operations.

Boeing operations research analysts designed and implemented a virtual simulation test to assess the preliminary man-machine interface for the Apache Longbow developed for the manned-unmanned teaming concept. The two week test was a part of an on-going Boeing internal research and development (IRAD) project aimed at exploring the effectiveness of teaming the Apache Longbow with unmanned air vehicles. The virtual simulation testing described in this paper was conducted in the AH-64D Engineering Development Simulator (EDS) at the Boeing Company in Mesa, Arizona.

OPERATIONAL CONCEPT

The initial IRAD focus is to develop a prototype manned-unmanned teaming capability for Apache Longbow. Based on the operational concept developed, the crew employs the UAV once it is in the mission profile. The crew does not takeoff, land, or "fly" the UAV. Conceptually the manned aircraft crew would employ one of three levels of UAV control. These levels of control include:

- Associated Mode. UAV navigation and sensors are controlled by a ground station. The manned aircraft crew is able to view UAV sensor video. The crew has no control over the UAV.
- Dedicated Mode. UAV navigation and sensors are controlled by a ground station. However, the ground crew responds directly to manned aircraft taskings. The manned aircraft crew is able to view UAV sensor video.
- Coupled Mode. UAV navigation and sensors are under direct control of the manned aircraft crew.

The focus of this test was assessment of the man machine interface. Therefore, the test scenario was limited to employment of the coupled mode to fully task the crew during the test. Further study and assessment of employment modes and their effectiveness is recommended, as it was not within the scope of the activity discussed in this paper.

Presented at the American Helicopter Society 54th Annual Forum, Washington, DC May 20 - May 22, 1998.

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

AH-64D MAN-MACHINE INTERFACE

The existing AH-64D Apache Longbow crewstation design was modified to provide a man-machine interface for operation of UAV navigation equipment, sensors and air vehicle systems for employment in the manned-unmanned teaming concept. This section provides a brief description of the UAV controls and displays that were integrated into the EDS crewstations.

The preliminary man-machine interface design incorporates current sensor, flight, and operational capabilities of both the Apache Longbow and the Hunter UAV, manufactured by TRW and IAI. Functional requirements for the man-machine interface were developed by Boeing operations research analysts and were based on the operational concepts developed under the IRAD. The Boeing design team included crewstation design engineers, an engineering test pilot, software engineers and operations research analysts. A TRW software engineer and UAV training and mission specialist were consulted by the team throughout the project.

UAV Controls and Displays

UAV controls and displays are integrated into the multifunction displays (MFDs) in both crewstations and into the Optical Relay Tube (ORT) controls in the Co-Pilot Gunner (CPG) crewstation. MFD controls are consistent with the current AH-64D controls and displays philosophy and allow for establishing a communication link to monitor and/or control the UAV and sensors, as required. The primary control of the UAV Multi-mission Optronics Stabilized Payload (MOSP) sensors is allocated to the CPG station via the ORT handgrips (Figure 1).

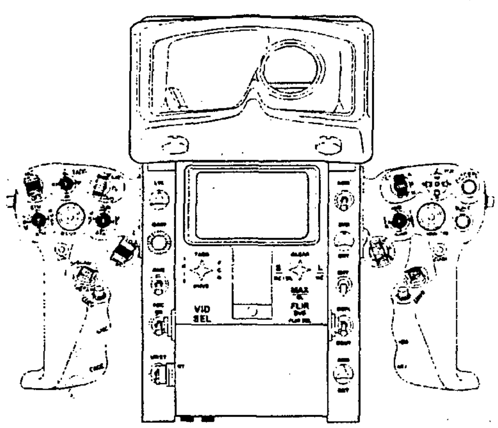

Figure 1. CPG Optical Relay Tube (ORT)

UAV Control Functionality

UAV sensor video is typically presented on the UAV page on the MFD overlaid by a minimum of UAV control buttons and sensor targeting/UAV flight parameter status information (Figure 2). UAV sensor video may also be presented under any MFD page format in the same manner as any AH-64D sensor video is currently displayed. UAV sensor video may be displayed to the CPG on the ORT video display as well. Symbology regarding UAV position and sensor orientation is also displayed on the MFD Tactical Situation Display (TSD) page (Figure 3). UAV symbology was not fully integrated into the TSD in time for this test. Further assessment is recommended once the integration is completed.

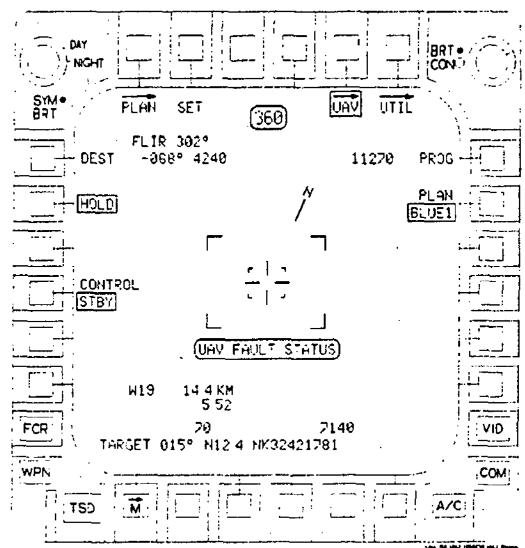

Figure 2. UAV Page

UAV sensor video may be monitored by one or more aircraft by enabling the UAV receiver/transmitter (R/T) on the appropriate channel. While sensor video imagery may be monitored in either crewstation and by other Apache Longbow team members, only one Apache Longbow is in control of the UAV at any one time during a mission.

Once the R/T has been enabled and a downlink established, one of two control modes may be selected by the crew to enable the uplink and control of the UAV. When control mode - *standby* is selected, the crew may select one of three UAV flight modes. However, control of UAV sensors is not enabled. Flight control of the UAV is via command inputs to the UAV auto-piloting system.

The UAV can be commanded to fly one of three flight modes:

- Plan mode. UAV flies one of six programmed mission plans.
- Destination mode. UAV flies to a specific waypoint with sensors oriented to a specific target.
- Hold mode. UAV flies a holding pattern at the current location with the sensors oriented to a specific target

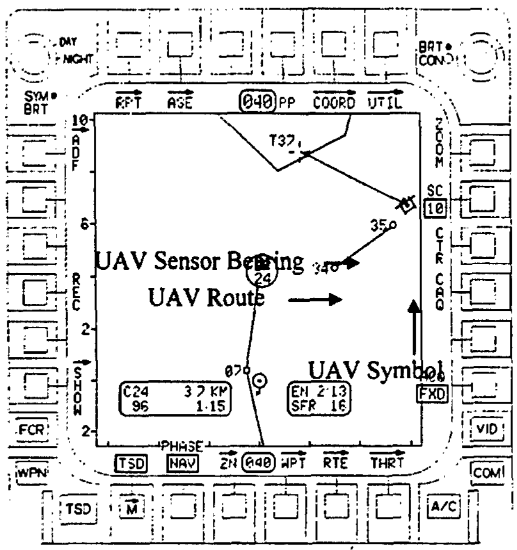

Figure 3. TSD Page

When control mode - *on* is selected, the crew has control of the UAV sensors as well as the UAV flight mode. By toggling between *standby* to *on* using either an ORT right handgrip control or a UAV page control, the CPG has immediate control over either the TADS or UAV sensors, as desired. UAV sensors are employed using the same ORT switch controls that are used to operate the AH-64D Target Acquisition Designation Sight (TADS) sensors. Based on the UAV control mode, these controls will operate either the TADS sensors (control mode *standby*) or the UAV sensors (control mode *on*). These functions include the capability to:

- select sensors and fields of view
- record sensor video imagery
- manually track targets
- lase targets to obtain range for target store data or for weapons engagement

As with other Apache Longbow systems, control settings and programmed mission data associated with the UAV and sensors will be entered into the data transfer cartridge at the Aviation Mission Planning Station (AMPS) and ultimately uploaded to the mission processors via the data transfer receptacle. This data is capable of being modified as necessary during flight.

DESCRIPTION OF TEST

This test had three objectives: (1) Assess the preliminary man-machine interface; (2) Collect limited objective data to address mission effectiveness; and (3) Provide initial data to be used to further develop conceptual Tactics, Techniques and Procedures (TTP).

Test Facilities

The two week assessment was conducted at the Apache Longbow Engineering Development Simulator (EDS), located at the Boeing-Mesa facility. It consists of pilot and CPG crewstations, each located in a separate 20 foot dome. Each crewstation is configured to represent the Apache Longbow crewstation design and is provided with baseline AH-64D functionality, an out-the-window visual display, sensor display, flight dynamics, and interaction with the central Tactical Mission Computer System (TMCS). The TMCS provides weapons and sensor capabilities, controls the threat, and accounts for all engagements involved in a tactical situation.

Test Subjects and Training

Four test subjects, all AH-64D Apache Longbow qualified and current pilots, participated in the study. Three participants were U.S. Army instructor pilots assigned to A Company, 1/14 Aviation Regiment, located at the Boeing facility in Mesa, Arizona and one pilot was a Boeing company test pilot.

Test subjects received training concerning the manned-unmanned teaming concept and the man-machine interface prior to conduct of the test runs. Training consisted of four hours of academic instruction and three 1.5 hour periods of simulator flight instruction. The same terrain and threat database were employed for training and test runs. However, different scenarios and supporting graphics, as well as the UAV flight route, were employed during training in order to minimize the impact of learning effect on the test runs.

Simulation Test Environment

The test was conducted using the standard Combat Simulation System Evaluation (CSSE) central European terrain database. This database consists of rolling terrain populated by villages, streams and forest tree blocks. The missions took place during daylight conditions. The threat consisted of elements of a Motorized Rifle Battalion deployed for attack.

The test was conducted in a part-mission environment. Initial conditions positioned the aircraft at the start point of the mission with all systems operational. The test consisted of eight simulator runs, with each of the four test subjects completing two test runs each. Each test subject flew as the CPG and used the modified man-machine interface design developed for manned-unmanned teaming. A Boeing simulator pilot flew in the pilot station for each of the test runs.

One vignette was used for the test. The crew was tasked to perform zone reconnaissance while employing a UAV for surveillance of an area adjacent to the zone. The CPG was required to receive handover of UAV control from the ground control station, verify UAV sensor operation, and assign the UAV a preplanned route for the mission. The aircraft then departed for the reconnaissance. During the mission, the CPG was tasked to conduct surveillance of specific areas of interest using both the organic TADS sensors and the UAV sensors. Normal voice and data radio traffic was simulated to increase task loading. The test vignette overlay is provided in Figure 4.

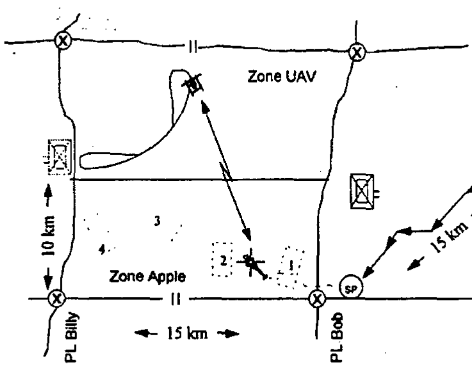

Figure 4. Test Vignette Overlay

Standard U.S. Army nap of the earth (NOE) operations and Tactics, Techniques and Procedures (TTP) as described in FM 1-112, *Attack Helicopter Operations* and FM 1-117, *Air Reconnaissance Squadron* were employed.

Conduct of Trials

Prior to each test run, each test subject and the Boeing simulator pilot received a mission briefing to understand the tactical scenario and objectives of the test. Each test run started with the test subject sitting in the cockpit wearing normal flight gear. The flight helmet and helmet mounted display were not worn by the test subjects, as these components were not a factor in the evaluation of the man-machine interface. Initial conditions for the EDS placed the aircraft on the ground running at the start point of the ingress route. The EDS pilot and CPG crewstations were operated in an integrated mode to permit the CPG test subject and Boeing simulator pilot to function as a single AH-64D crew.

RESULTS

The results of this test include subjective and objective data. Subjective data were collected to address the adequacy of the man-machine interface as well as to provide a limited assessment of the concept of linking a UAV to a manned rotorcraft. Objective data were collected from observations tracked during the trials and real-time data collection from the Apache Longbow EDS. These data were used to assess the functionality of the design and to support the limited assessment of the concept.

The data were gathered from data recorders, task performance tracking sheets, notes taken during the trial, pilot questionnaires, and mission debriefs. Pilot opinions regarding positive and negative attributes of the display formats and symbology, observations concerning the operational difficulty using the interface, and operational employment were of key interest.

Objective Data

<u>Crew Task Performance</u>. Performance of UAV control tasks were monitored during each trial and errors were counted using a tracking sheet. The objective was to identify tasks with higher levels of difficulty based on the error counts. Tasks with higher error counts may indicate a need to further assess design features and functionality to reduce the difficulty associated with performance. As shown in Table 1, the tasks which the crew had the greatest difficulty performing were: manually searching, manually tracking, (in narrow and zoom fields of view only) and slaving the UAV sensor to the target. Because manual search and manual track are not

discreet tasks, a weighting scale was developed to rate the performance of these tasks for counting as errors. The higher number of task errors for these two tasks should be weighed against the fact that search and track tasks were performed far more than any other tasks. Design functions supporting manual search and manual tracking should be more closely examined during completion of the man-machine interface integration effort and re-assessed in future studies.

Table 1. Summary of Crew Error Tracking

Task Area	Total # of Errors
Perform UAV Initialization	0
Perform UAV Handover	0
Perform UAV Navigation	1
Perform UAV Sensor Operational Checks	0
Perform UAV Sensor Manual Search	6
Perform UAV Sensor Manual Tracking	15
Perform UAV Sensor Target Slaving	4
Perform TADS UAV Target Acquisition	0
Perform UAV LRFD Operations	0
Perform UAV Target Storing	0

Operational Measures of Effectiveness. Limited data were collected to make a preliminary assessment of the effectiveness of the manned-unmanned teaming concept. Objective real-time data were captured for six of the eight trials. The measures of effectiveness for the test and results are described below.

- UAV Target Detection Range. The average distance from Apache to the threats when the threats are visually detected by UAV sensors was 13.4 km. However, it would not have been possible for the crews to detect threats beyond 20 kilometers due to the nature of the test scenario. Although the objective was not to see how far or how quickly the crews would detect threat, it is still worth noting that crews detected threats beyond the organic sensor capabilities of current attack and reconnaissance rotorcraft.
- Number of Targets Acquired. The total number of possible targets was seven. However, the actual number presented to a crew during a trial varied due to EDS image generator performance. Regardless of the number of targets presented, once the crew detected the threats using UAV sensors, all threats were acquired.
- Exposure Time. In all but one of the trials, Apache was not exposed to threat line-of-sight. During the one trial in which Apache was exposed, the exposure time was approximately 11 seconds in duration at a range of 9.7 km from the threat.

Subjective Data

The primary purpose for collecting subjective data was to document pilot feedback concerning the acceptability of the preliminary man-machine interface. A questionnaire was developed with four areas of consideration for the design, to include:

- Presentation of Data
- Design Functionality
- Design Utility
- Crew Workload

Subjective data concerning operational concepts were also gathered.

Presentation of Data, Design Functionality, Design Utility. Following each of the test trials, the test participants were asked to rate the acceptability of the man-machine interface. The rating scale for these data are 1.0 to 5.0, with 1.0 "terrible/of no use" and 5.0 being "excellent/extremely useful". The ratings were then compiled to present an overall picture of the man-machine interface acceptability. Figure 5 presents the average scores of the interface, rated by the subject pilots in four (4) areas of concern: (1) UAV Handover and Set-up phase; (2) UAV Sensor Operations; (3) UAV Status; and (4) Overall Concept Summary. This figure is a graphical representation of the tabular results.

As shown in Figure 5, average ratings exceeded 4.0 (good/of considerable use) in all four areas of consideration. From a total of 59 questions, seven rated in the 3.0 to 3.9 acceptability range (only fair/of use), and no ratings were received below the 3.0 acceptability range. The two questions/categories which rated the lowest were "Rate your situational awareness of a UAV real time position relative to your Apache location." receiving an average score of 3.5 and "Rate the usefulness of modifying UAV altitude.", receiving an average score of 3.4. The questions or areas receiving the highest ratings were "Rate the utility of UAV sensor video underlay on the MFD.", scoring an average of 4.8, "Rate the usefulness of viewing UAV video on the MFD - UAV page.", scoring an average 4.8, and "Rate the usefulness of the UAV hold mode", receiving a 4.9 average score.

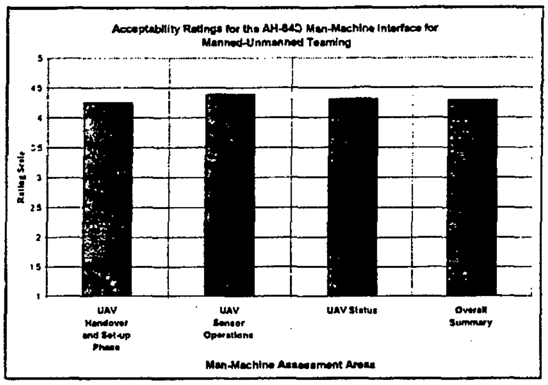

Figure 5. Man-Machine Interface Ratings

Pilot comments/suggestions concerning the design acceptability were gathered during the mission debriefs. Pilot comments were mainly concerned with presentation of data on the TSD and UAV sensor tracking. The most common comments concerning the TSD were suggestions to include the UAV location/bearing and UAV route on the TSD. These features are a part of the preliminary design, but were not integrated in time for the virtual simulation test. As these features are integrated into the design, additional study and assessment is recommended. With regard to UAV sensor tracking, two pilots expressed difficulty with tracking in narrow/zoom fields of view. These comments are consistent with the objective data concerning target acquisition and tracking noted in the previous section. Further investigation into integration of the UAV sensor tracking capabilities in the man-machine interface is recommended.

Work Load Assessment. A modified Task Load Index (TLX) was used to assess crew workload in relation to the acceptability of the man-machine interface. Figure 6 presents the subject ratings in six areas of task loading. The rating scale for these data are 1.0 to 10.0, with the lower score of 1.0 representing minimal work load and a rating scale of 10.0 representing task saturation. A rating scale of 1.0 to 10.0 is used versus a scale of 1.0 to 5.0 to provide the necessary granularity for accurate measures. The rated areas are as follows:

(1) Mental demand. How much mental and perceptual activity was required.

(2) Physical demand. How much physical activity was required.

(3) Temporal demand. How much time pressure was felt by the subject due to rate or pace at which the tasks or task elements occurred.

(4) Performance. How successful the subjects felt they were in accomplishing the goals of the task set by the experimenter (or themselves).

(5) Mental and Physical effort. How hard the subjects felt they had to work (mentally and physically) to accomplish their level or performance.

(6) Frustration. How insecure, discouraged, irritated, stressed and annoyed versus secure, gratified, content, relaxed and complacent the subjects felt during the task.

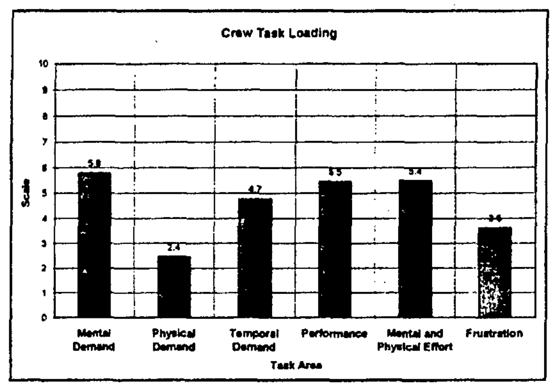

Figure 6. Crew Task Loading

As shown in Figure 6, the areas which the crew felt the highest demand were: (1) Mental Demand; (2) Performance; and (3) Mental and Physical Effort. The scores for these areas were between 5.0 and 6.0, well below the score of 10.0 which would represent a high demand on the crew member. The data compiled from the Task Loading questionnaire resulted in an average score of 4.6. According to the numerical ratings given and based on interview comments, the test subjects did not experience any task overload using the man-machine interface to employ the manned-unmanned teaming concept.

Pilot subject comments concerning work load reveal that they did not feel that they experienced task saturation or work overload. Comments also stated that with each day, the system was easier to use and with more experience, tasks relating to the interaction with a UAV would come naturally. One subject commented, "There was no added work load specifically due to the UAV. I received IDM traffic, radio calls, but you just prioritize tasks like if you were using your TADS. No difference with UAV sensors as with TADS . . ."

Pilot Comments Concerning Concept of Operations. Specific questions were asked the test subjects during the debriefing of each test run to obtain aircrew feedback and to ferret out new ideas for the manned-unmanned teaming concept. Test subject comments are summarized below.

- UAV Distance During Reconnaissance. Subjects felt that the optimum position for the UAV during Apache reconnaissance/security missions would be approximately 10 km in front of or to the flank of the Apache.
- UAV Control During Reconnaissance. Direct control of the UAV by the manned aircraft is most suitable when the UAV is providing security for an attack/reconnaissance mission. When the UAV is performing reconnaissance in an area adjacent to the manned aircraft as an economy of force, however, control should be maintained by the UAV ground control station. The Apache crew can still monitor the UAV video live feed without direct control.
- Applicability of UAV During Movement to Contact. The UAV may be very well suited as a remote sensor during movement to contact missions. One subject commented, ". . . turns a movement to contact into a deliberate attack. . . . allows you to almost remove a movement to contact as a scenario." Hence, the UAV makes the 'contact', and the manned aircraft conducts the deliberate attack.

CONCLUSION

The Boeing Company has performed an early assessment of the preliminary man-machine interface for developed for teaming the AH-64D Apache Longbow with an unmanned air vehicle in a virtual simulation environment. This man-machine interface is based on existing AH-64D crewstation design and UAV operational and functional characteristics.

(1) Subjects rated the acceptability of the man-machine interface as at least "good" in terms of Presentation of Data, Design Functionality, and Design Utility.

(2) Subjects did not experience any task overload using the man-machine interface during test runs.

(3) Objective and subjective data indicate that subjects did experience some difficulty with manual target search and tracking in the narrow and zoom fields of view.

(4) A limited assessment of operational measures of effectiveness indicate that the manned-unmanned teaming concept has the potential to allow crews to acquire targets beyond the range of organic sensors without being exposed to threat forces.

(5) Subject comments indicate that the manned-unmanned teaming concept has applicability for attack and reconnaissance missions.

(6) UAV sensor tracking and target acquisition features should be examined as the design is completely integrated.

(7) Further studies and assessments should be performed once the complete preliminary man-machine interface is integrated into the AH-64D crewstation.

(8) Further study of the manned-unmanned teaming concept to include mission effectiveness and employment modes is recommended.

Flight Control Law Design and HIL Simulation of a UAV

(April 1999)

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Keywords:

Eigenspace assignment, gain scheduling, flight control, UAV.

1 Summary

An adaptive control methodology, merging two known approaches to flight control problem, gain-scheduling and direct eigenspace assignment (DEA), is developed. A gain-scheduled inner (stability) loop structure is shown to minimize the variance of the outer (guidance) loop gains and increase the robustness of the system. The employment of DEA with gain scheduling is observed to decouple the longitudinal and lateral flight modes resulting adequate system stability, enhanced robustness and control surface effectiveness. This methodology is used in the flight control law design of a UAV.

2 Introduction

Employment of eigenvalue / eigenstructure assignment techniques has found widespread practical applications that solve a variety of flight control problems. Digital implementation of these applications has evolved to be commonplace by the recent advances in microprocessor technology.

In this paper, two known approaches to the flight control design, gain scheduling and eigenspace assignment are reviewed. In the third and fourth sections, two methods are explained with their formulations, respectively. In section five the flight control problem is stated and developed scheme is presented to solve the problem, to demonstrate synergetic use of these two methods. Section six discusses the results achieved.

3 Gain Scheduling

In many situations it is known how the dynamics of a process change with the operating conditions of the process. One source for the change in dynamics may be the nonlinearities that are known. It is then possible to change parameteres of the controller by monitoring the operating conditions of the process. This idea is called gain scheduling. It can be regarded as a special kind of nonlinear open-loop adaptation of regulator parameters in a preprogrammed way. Gain scheduling is easy to implement in computer controlled systems provided that there is support in the available software. This is an ad hoc practice guided by heuristics rule of thumb [lev].

A main problem in the design of systems with gain scheduling is to find suitable scheduling variables. This normally done based on knowledge of the physics of a system. The concept of gain scheduling originated in connection with the development of flight control systems (FCS). In FCS applications, generally the Mach number and the dynamic pressure are measured by air data sensors and used as the scheduling variables. In this paper only the dynamic pressure is used as the scheduling variable since the air vehicle to be controlled has a relatively narrow speed envelope. Figure 1. shows the gain scheduling scheme, which can be viewed as a system with feedback gains adjusted using feedforward compensation.

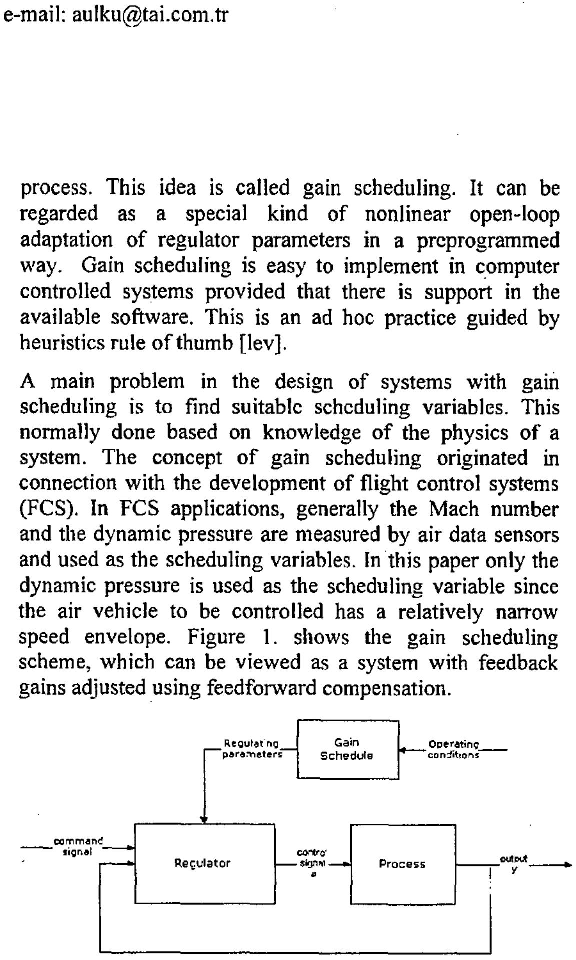

Figure 1. Gain scheduling

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

4 Direct Eigenspace Assignment

4.1 Background

Eigenstructure assignment is a useful tool that allows the designer satisfy damping, settling time, and mode decoupling specifications by choosing eigenvalues and eigenvectors. Moore [moo] in 1976 and Shrinathkumar [shri] in 1978 made the first discussions on this approach. Andry et al. [andr] have applied eigenstructure assignment to designing a stability augmentation system for lateral dynamics of L-1011 aircraft in 1983. Sobel and Shapiro [sobe1] used this method to design dynamic compensators for the same aircraft in 1984. Later Sobel et al. [sobe2] proposed an systematic method for choosing elements of the feedback gain matrix which can be suppressed to zero with minimal effect for and F-18 HARV on assignment. Kautsky et al. [kaut] proposed some robustness measures for system eigenvalues to be least sensitive to parameter variations. Direct Eigenspace Assignment (DEA) method was developed in 1986 by Davidson and was used to design lateral-directional control laws for F-18 HARV of NASA in 1992. This method allows designers to shape the closed loop response by direct choice of both desired eigenvalues and eigenvectors. It is called "direct" because unlike some eigenstructure assignment algorithms feedback gains are determined in a single iteration. Davidson et al. [davi1] has shown that during this effort DEA has been demonstrated to be a useful technique for aircraft control law design and issued some guidelines for lateral-directional flying qualities for high performance aircraft [davi2] in 1996.

4.2 DEA Formulation

Given the observable, controllable system

$$\dot{x} = Ax + Bu\,,\ x \in R^{n}\,,\ u \in R^{m} \tag{4.1}$$

and

$$y = Cx + Du\,,\ y \in R^{k} \tag{4.2}$$

The total control input is the sum of the augmentation input u_c and pilot's input u_p

$$u = u_p + u_c \tag{4.3}$$

The measurement feedback control law is

$$u_c = Gy \tag{4.4}$$

Solving for u as a function of the system states and pilot's input yields

$$u = \left[I_m - GD\right]^{-1} GCx + \left[I_m - GD\right]^{-1} u_p \tag{4.5}$$

The system augmented with the control law is given by

$$\dot{x} = (A + B\left[I_m - GD\right]^{-1} GC)x + B\left[I_m - GD\right]^{-1} u_p \tag{4.6}$$

The spectral decomposition of the closed loop system is given by

$$(A + B\left[I_m - GD\right]^{-1} GC)v_i = \lambda_i v_i \tag{4.7}$$

for $i=1,\dots,n$ where λ_i is the i[th] system eigenvalue and v_i is the associated i[th] system eigenvector. Let w_i be defined by,

$$w_i \equiv \left[I_m - GD\right]^{-1} GCv_i \tag{4.8}$$

Substituting this result into equation 4.7 and solving for v_i one obtains

$$v_i = \left[\lambda_i I_n - A\right]^{-1} Bw_i \tag{4.9}$$

This equation describes the achievable i[th] eigenvector of the closed loop system as function of the eigenvalue λ_i and the eigenvector w_i. By examining this equation one can see that the number of control variables (m) determines the dimension of the subspace in which the achievable eigenvectors must reside.

Values of w_i that yield an achievable eigenspace that is as close as possible in a least squares sense to a desired eigenspace can be determined by defining a cost function values associated with the i[th] mode of the system

$$J_i = \frac{1}{2}\left[v_{a_i} - v_{d_i}\right]^{H} Q_{d_i}\left[v_{a_i} - v_{d_i}\right] \tag{4.10}$$

for $i=1,\dots,n$ where v_{a_i} is the i[th] achievable eigenvector associated with eigenvalue λ_i, v_{d_i} is the i[th] desired eigenvector and Q_{d_i} is an n-by-n symmetric positive semi-definite weighing matrix on eigenvalue elements, ^{H} denotes the complex conjugate transpose operator. This cost function represents the error between the achievable eigenvector and the desired eigenvector weighed by the matrix Q_{d_i}.

Values of w_i that minimize J_i are determined by substituting (4.9) into cost function for v_{a_i}, taking the gradient of J_i with respect to w_i, setting this result equal to zero, and solving for w_i. This yields

$$w_i = \left[A_{d_i}{}^{H} Q_{d_i} A_{d_i}\right]^{-1} A_{d_i}{}^{H} Q_{d_i} v_{d_i} \tag{4.11}$$

where

$$A_{d_i} = \left[\lambda_{d_i} I_n - A\right]^{-1} B \tag{4.12}$$

By concatenating the individual w_i's column-wise to form W and v_{a_i} column-wise to form V_a equation can be expressed in matrix form by

$$W = [I_m - GD]^{-1} GCV_a \qquad (4.13)$$

The feedback gain matrix that yields the desired closed loop eigenvvalues and achievable eigenvectors is given by

$$G = W[CV_a + DW]^{-1} \qquad (4.14)$$

4.3 DEA Design Algorithm

A feedback gain matrix that yields a desired closed loop eigenspace is determined in the following way [davi1]:

1. Select desired eigenvalues λ_{d_i}, desired eigenvectors v_{d_i} and desired eigenvector weighing matrices Q_{d_i}.
2. Calculate w_i's using equation 4.11 and concatenate these column-wise to form W.
3. Calculate achievable eigenvectors v_{a_i}'s using equation 4.9 and concatenate these column-wise to form V_a.
4. Calculate feedback gain matrix G by equation 4.14.

5 System Design

5.1 Methodology

In Figure 4. system design is depicted. System states for longitudinal control system are X = [V, α, q, θ, h]; airspeed, angle of attack, pitch rate, pitch angle and altitude. Objective is to design both the altitude-hold and the speed-hold autopilots for this system. The related plant inputs are U = [δ_e, δ_T]; elevator and throttle deflection. Piloted command inputs are desired speed and desired altitude. Thus, theoretically, four gains are required for the elevator inner loop feedback, another four is required for the throttle inner loop feedback.

After determining a particular flight condition, the desired inner loop closed loop eigenvalues and vectors; the DEA algorithm of section 4.3 was utilized in order to calculate the feedback gains required for the inner loop compensators. The DEA algorithm in section 4.3 was coded in XMATH™ script to enable the designer to repeat this process for all 27 flight conditions, within a few seconds for each condition. In this application dynamic pressure Q was selected as the scheduling variable, which is $0.5\rho V^2$, where ρ is the air density in kg/m^3 and V is the total airspeed in m/sec. This automatic gain calculation process was succeeded by plotting each gain versus the dynamic pressure of the corresponding flight condition.

All eight gains were plotted against dynamic pressure and these were fit to polynomials to yield gain formulas as a function of dynamic pressure. Four of these gains are shown in Figure 3-a to 3-d. Plots show that all the longitudinal gains vary non-linearly and tend to decrease in absolute value with increasing dynamic pressure.

The PI controller gains K_{P1}, K_{I1}, K_{P2}, K_{I2} were then calculated by the Ziegler-Nichols closed-loop method [astr] and lastly, the rate of climb adjust K_{ALT}, determined by trial and error for the best rate of climb.

5.2 Inner Loop Controller

The microcontroller based controller consists of gain scheduler, which infact resides as a module inside the flight management software, dynamically calculates the elevator demand in the following scheme:

1. Calculate air density: $\rho = \rho_0(1 - 0{,}00002256h)^{4.256}$
2. Calculate dynamic pressure: $Q = \frac{1}{2}\rho V^2$
3. Using the gain equations that fit the gain plots (Figures 3.a thru 3.d), calculate the gains K_V, K_α, K_q and K_θ.
4. Calculate Elevator demand:

   δe-demand = θ-demand + $K_V.V + K_\alpha.\alpha + K_q.q + K_\theta.\theta$

The similar effort is performed for the throttle control loop. Altitude and speed gains are calculated, by the controller according to the maximum and minimum rates of climb and forward acceleration specifications respectively.

5.3 HIL Simulation

Hardware in the loop simulations were performed on a non-linear aircraft model that covers the complete flight envelope in MATRIX-X/AC-100™ environment. Control system of Figure 4. was employed. Sensor were modeled and the control system (the DSP processor) is added into the system loop. A 100 m climb demand was given to the system while the vehicle was in equilibrium, (cruising at 60 m/s, with trimmed angle of attack and pitch angle of 1.8°, at 1000 m altitude) at 10th second. Altitude, pitch angle, angle of attack, speed, throttle and elevator demands were observed. For longitudinal control design an acceptable climb performance (approx. 4 m/s) is achieved in the cruise speed of 60 m/s. Control surfaces move in a moderate speed and within limits. (see Figures 2-a, 2-b, 2-c).

6 Conclusion

Direct eigenspace assignment is used guarantee the inner loop stability of the closed loop system. As for longitudinal control, short period and phugoid modes are damped to the same nominal prescribed frequency and damping factor values for all flight conditions so that compensated system shall appear identical poles in all conditions. This gives the designer the opportunity to design the outer loop easier without employing any further gain schedule for the rest of the system. Design philosophy is simply, parametrization of the inner loop gains via dynamic pressure so that the the inner loop dynamics always appear almost the same to the outer guidance controller dynamics.

Gain scheduling had a positive effect on control surface effectiveness and robustness. DEA had positive effects on overall stability of the system. These two methods have been merged successfully to yield a high performance controller that employs the advantage of each method.

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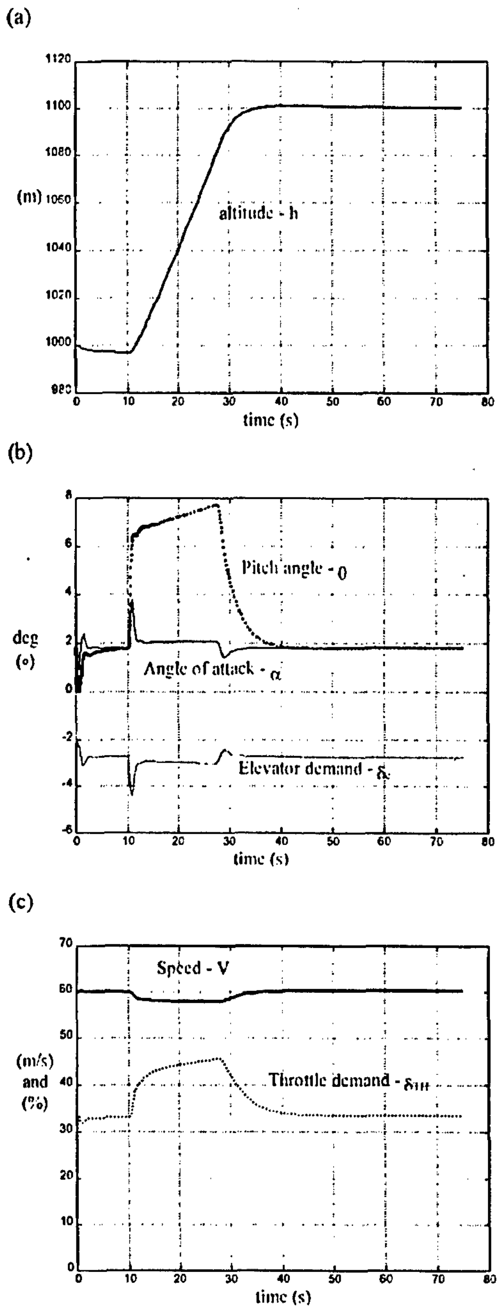

Figure 2. Controller in-the-loop system response to 1000 m climb demand

(both altitude-hold and speed-hold autopilots ON)

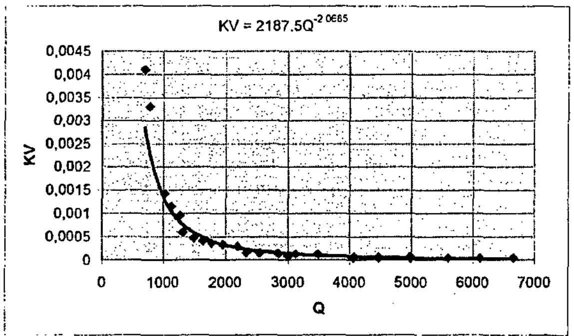

Figure 3-a. Gain vs. dynamic pressure plot and approximate curve fit with its equation for K_V

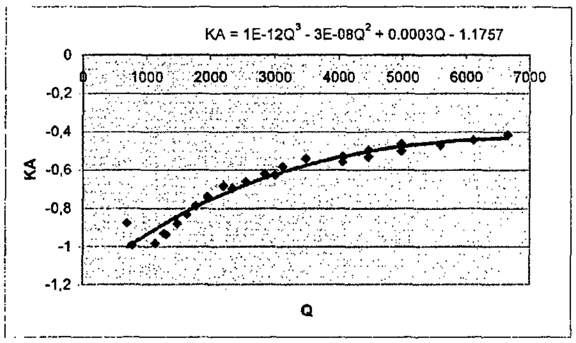

Figure 3-b. Gain vs. dynamic pressure plot and approximate curve fit with its equation for K_α

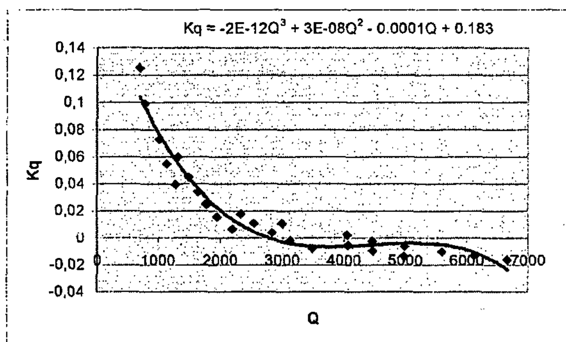

Figure 3-c. Gain vs. dynamic pressure plot and approximate curve fit with its equation for K_q

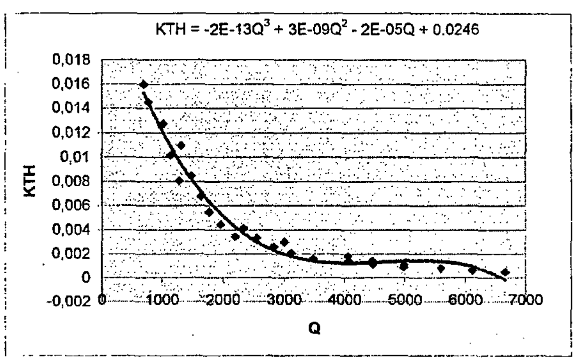

Figure 3-d. Gain vs. dynamic pressure plot and approximate curve fit with its equation for K_θ

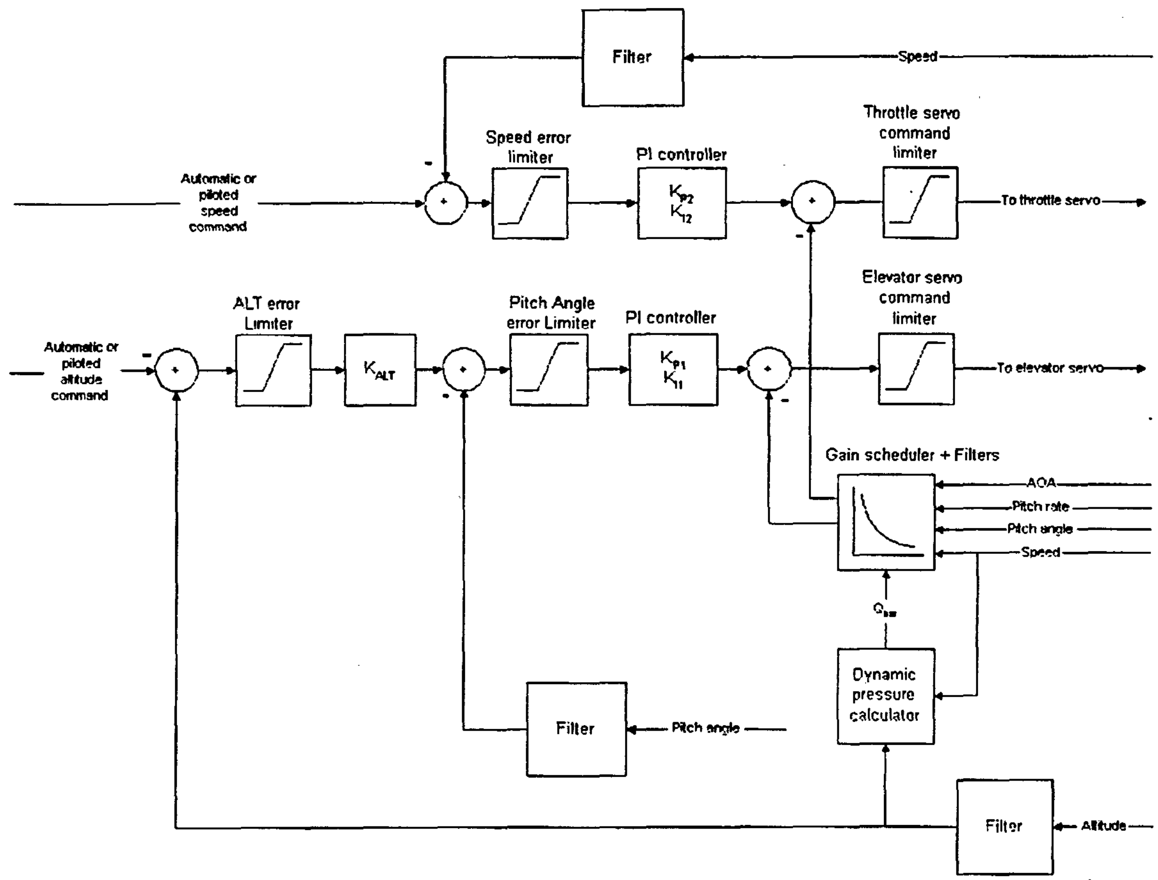

Figure 4. Longitudinal Control System Design

UNMANNED RESEARCH VEHICLE (URV): DEVELOPMENT, IMPLEMENTATION, & FLIGHT TEST OF A MIMO DIGITAL FLIGHT CONTROL SYSTEM DESIGNED USING QUANTITATIVE FEEDBACK THEORY

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Abstract

The Quantitative Feedback Theory (QFT) design technique, which has the ability to bridge the gap between theory and the real-world control design problem, is utilized in the design of a MIMO digital flight control system for an unmanned research vehicle (URV) that is presented in this paper. The design illustrates how the "real-world" knowledge of the plant to be controlled and the desired performance specifications can be utilized in trying to achieve a successful robust design for a nonlinear control problem. This paper presents some of the issues involved in developing, implementing, and flight testing a flight control system (FCS) designed using QFT. Achieving a successful FCS involves a number of steps: specification of the control problem, aircraft model data, theoretical flight control system design, implementation, ground testing, and flight test. The last three steps embody the "practical engineering" aspects that are vital to achieving a successful FCS. The main emphasis of this paper is on these steps. First, there is a brief explanation of the MIMO design QFT process. This is followed by a description of the steps involved in the implementation and testing of a QFT designed FCS. Thus, this presentation provides an overview of "using robust control system design to increase quality" in attempting to demonstrate the "Bridging the Gap" between control theory and the realities of a successful control system design. In facing the technological problems of the future, it is necessary that engineers of the future must be able to *bridge the gap*, i.e., this "Bridging the Gap" must be addressed to better prepare the engineers for the 21st century.

I INTRODUCTION

In facing the technological problems of the 21st century, it is necessary that engineers of the future must be able to *bridge the gap* between the scientific and engineering methods. Developing a set of Engineering Rules (E.R.) is a first step towards achieving this goal (see Chap. 9 of ef. 1). This paper provides the next step in enhancing this goal: overcoming problems encountered during design, implementation, and achieving a successful real world QFT designed FCS control system. The QFT technique is a design method that has the inherent capability to assist in bridging the gap between the scientific and engineering methods. Thus, a discussion of the development, implementation, and successful flight test of a flight control system, designed using QFT techniques, is presented in this paper. The robust flight control system was designed for and flown on the Lambda Unmanned Research Vehicle (URV. Lambda is a remotely piloted aircraft that is operated by the Air Force Research Laboratory at Wright-Patterson AFB, OH for research in flight control technology.

Control design problems generally involve real world nonlinear plants. In utilizing control system design techniques, which require linear plant models, it is necessary that assumptions be made that allow simplification of these nonlinear plants, i.e., "assume linear behavior" that result in obtaining linear plant models. Thus, it is important for the designer to follow a design and implementation process that allows the testing of the assumptions as early in the process as possible so the control system can be redesigned, for example, to take into account unmodeled effects. As detailed in this paper, the control design process should include simulation of the control system on increasingly realistic models which helps transition to implementation on real world applications. Most of the real world implementation problems are the result of assumptions made during the design process.

II OBJECTIVE

The objective of this project was twofold. First, develop a robust flight control system using QFT, and take the de-

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

sign through a flight test. Second, implement an inner loop FCS on the Lambda URV that would be part of an autonomous flight control system. During the project the first objective was accomplished and then, because of hardware improvements, a second design was developed and flight tested. This second design was accomplished to better meet the requirements of the second objective. The FCS design process used is shown in Fig. 1. As indicated by the arrows in the one complete FCS design cycle covers the process through the flight test and then back to the redesign stage. During this project there were four cycles around this loop. Two of the cycles produced unsuccessful flight tests and two produced successful flight tests.

III. QFT DESIGN PROCESS[1-4]

The QFT technique requires that $\iota = 1,2,3,\ldots,J$ LTI models be determined that represent the dynamical model over its operating scenario in order to achieve a robust design. These LTI plants determine the template contours which represent the region of plant parameter uncertainty and are used in the QFT design technique. The robust digital flight control system design was performed as a psuedo-continuous-time (PCT) control system. Upon completion of the design the compensators and prefilters are transformed into the z-domain controllers and prefilters by use of the Tustin transformation.

IV CONTROL SYSTEM DESIGN PROCESS (FIG. 1)

In order to design a control system for a real world control problem, the designer must follow a design process such as that shown in Fig. 1. This figure represents a design process that moves the designer from the problem definition stage to the successful control system implementation in steps of increasing reality. If the control system does not meet performance specifications at any stage of the process, the control system is redesigned and retested. In general, as the simulations become more realistic, they also become more expensive both in cost and time. Therefore, it is very important to be able to find potential problems early in the design process for the control system. The ovals inside the circle in Fig. 1 indicate the features of the QFT technique that assist in the design of control systems and can best meet performance specifications and be implemented on the real world system. The following sections describe the individual stages of the control design and implementation process. Indicated in the following sub-section titles is a number that refers to the block number in Fig. 1 to which the sub-section applies.

III-1 FUNCTIONAL REQUIREMENTS (#1)

The designer, at the onset, must have a clear understanding of the problem that needs to be solved. That is, the designer must understand what the controlled system is required to do and what are its operational requirements. The designer must also understand the environment in which the system is required to operate, i.e., the environmental requirements. Together these two requirements make up what is referred to as the *functional requirements*. If the designer does not start with a clear understanding of the functional requirements, costly time can be wasted in the design-test-redesign cycle. If during the design process, it becomes clear that the functional requirements cannot be met, the designer might be called upon to use engineering judgement and the knowledge of the goals of the controlled system to modify these requirements. Note, this is not a step that a control designer normally takes on his own.

III-2 PERFORMANCE SPECIFICATIONS (#2)

Performance specifications[1,2] are essentially mathematical models developed from the functional requirements and are utilized during the design process in order to achieve the desired system performance robustness. Since performance specifications are normally only interpretations of the functional requirements, the designer must be aware of how the specifications and requirements relate and what tradeoffs need to be made. During the design process, the designer might need to apply engineering judgement in order to make the necessary modifications to the specifications that, while still meeting the requirements, enables achieving a robust control system design.

III-2.3 DYNAMICS MODEL (#3)

A *dynamic model* is a mathematical model of the system to be controlled and is developed from a knowledge of the system and its operating requirements. This model can be as simple as a linear-time-invariant (LTI) transfer function or a complicated set of nonlinear differential and algebraic equations with time varying parameters. In many cases, a simplified model of the dynamical system can be used to represent the system in the control design process. In fact, the designer should try to use as simple a model as possible that represents the important system dynamics in the design process. For example, from an analysis of the LTI transfer functions a designer may be able to determine their nondominating poles and zeros, i.e., those which have a negligible effect on the system's performance (those that lie outside the system's bandwidth). Thus, by deleting the nondominating poles and zeros from these LTI transfer functions reduced order models are obtained. Not only does a reduced order model simplify the design process, but also reduces the risk of introducing numerical inaccuracies in the design process. But remember, an oversimplified model can lead to trouble as in the case of bending modes as discussed in Sec. IX

III-2.4 CONTROL AUTHORITY ALLOCATION (#4)

An important part of the design process is the *control authority allocation* assigned to each of the control effectors. Depending on the dynamical system, there may be redundant control effectors, i.e. the number of control effectors available to the controller may be greater than the number of controlled variables. Also, the control effectors available may induce cross-coupling in the dynamical system and do not clearly control any one variable. In these cases, judgement must be exercised by the designer, based upon knowledge of the real-world operating characteristics of the plant, in determining the percentage of the control authority that is allocated to the various controlled variables. That is, a method for determining the percentage of control power available from each control effector to each controlled variable must be determined. The optimization of the control effectors' control authority allocation can be used to help decouple the system and assist in achieving the desired robust system performance. This control authority allocation is accomplished by the proper selection of the w_{ij} elements of the weighting matrix $\boldsymbol{W}$.

III-2.5 QFT CONTROL SYSTEM DESIGN (#5)

The QFT design process is used to develop mathematical algorithms that can be implemented in order to achieve the desired control system performance. Implementation issues and insights provided by the QFT process to the designer are discussed in the following sections. A QFT design can be accomplished by use of the MIMO QFT CAD package[5] which greatly simplify the design process.

III-2.6 LINEAR SIMULATION (#6)

Once the control algorithms have been designed, they are implemented along with linear representations of the dynamical system. These systems are simulated and the results are compared to the specifications. Since QFT design involves linearizing non-linear equations, the control system must be simulated for each of the J LTI transfer functions to check the result against the specifications. If some or all of the specifications have not been met, the designer can either redesign the control system or reexamine the requirements. In some cases, the initial specified requirements may not be realistic. For designs that involve control effector damage, the designer must ensure that the assumed percentage of effector damage is realistic with respect to its associated remaining control authority available to satisfy the control system performance requirements; for example, to still be able to fly the aircraft. Also, the designer must ensure that the system performance is close enough to the specifications to meet the overall functional requirements.

III-2.7 NONLINEAR SIMULATION (#7)

Once the control system has passed the linear simulation testing phase, the simulation complexity is increase by adding nonlinear components and any other components that are removed to simplify the simulation. As with the linear simulations it may be necessary to accomplish a redesign or a revaluation of the specifications (performance specifications, control authority allocation, and/or the percentage of control effector failure).

III-2.8 ENGINEERING VISUALIZATION (#8)

After each of the simulations it is valuable to animate, by a computer simulation, the dynamics data to better understand exactly what occurs during the simulation. Note that the three dimension engineering visualizations integrate all of the dynamics of the simulation. For example, in the case of an aircraft (A/C) this means that the designer can view the angle of attack, pitch rate, pitch attitude, forward velocity, vertical velocity, and altitude simultaneously. Instead of trying to decipher the position and attitude of the A/C from six two dimensional plots, the designer can obtain a clearer understanding from watching the computer animation of the maneuver. For more specific details of the maneuver the designer can then return to the data plots.

III-2.9 ENGINEERING INTERACTIVE SIMULATION (#9)

When there is an operator involved in the controlled system, for example, a pilot flying an A/C, it is often useful for the designer to use an interactive simulation in order to obtain a better understanding of the operation of the system. It should be noted in reality that the pilot is a part of the overall flight control system, i.e., he forms the "outer loop" of the control system. Thus, this type of control system is referred as a *manual flight control systems*. An interactive simulation provides the designer with the ability to implement the control system in the same fashion that it will be implemented on the dynamical system. The interactive simulation also gives the designer the ability to test the system continuously throughout the operating environment. In the case of a control system designed for an A/C, the interactive simulation involving a pilot gives the designer the ability to perform a simulated flight test before the design leaves her/his desk. Such simulations, for a specified A/C, are often performed by a pilot, for example, at the Wright-Patterson AFB Lamars simulator.

III-2.10 HARDWARE-IN-THE-LOOP SIMULATION / IMPLEMENTATION (#10)

At this stage of design and implementation the control system algorithms are implemented on the same type of hardware systems as those that control the dynamical system. Other hardware components such as actuators and sensors are also connected to the system. This allows simulation of real-time operation of control algorithm, noise corrupted measurements for feedback, and computation cycle time/sampling rate quantization errors. A hardware-in-the-loop-simulation is also useful to ensure that commands issued from the control system move the effectors in the correct directions and the outputs of the feedback sensors have the correct polarity.

III-2.11 OPERATOR-IN-THE-LOOP SIMULATION (#11)

In order to insure the controlled system meets the requirements of the human operator a simulation is set up to allow the operator to interact with a simulation of the system. Many of these simulations surround the operator with visual cues and some, inject motion into the simulation. These types of simulations are used to improve the handling qualities of the controlled system by giving the operator a chance to try out the controlled system and then using his or her responses to help shape a redesign.

III-2.12 SYSTEM TEST (#12)

The final testing of the control system involves implementation on the dynamical system and operational testing. Once the controlled system has been shown to meet the performance specifications for the operating environment, a successful control design has been achieved.

III-2.13 REDESIGN (#13)

At every stage of the control system design and implementation process the designer makes a decision to move to the next stage or to redesign (modify) the control system. Once the control system is modified the simulation testing is repeated.

IV DESIGN PROCESS EXAMPLE

The Lambda Unmanned Research Vehicle (URV) shown in Fig. .2 is a remotely piloted A/C with a wingspan of *14 ft* and is operated by the US Air Force for research in flight control technology. The objectives of the project described in this section are as follows:

1. To design robust flight control systems using the QFT design technique
2. To flight test these designs
3. To implement an inner loop FCS on the Lambda URV that would be part of an autonomous flight control system
4. To illustrate some of the real-world problems that are encountered in performing the control system design process shown in Fig. 1.

In accomplishing this design project required four cycles around the control design process loop. These four design cycles are:

Cycle 1 – This cycle involved the satisfaction of only the first two of the project objectives.

Cycle 2 – Cycle 1 was repeated but involved the design of an improved integrator wind-up limiter.

Cycle 3 – A redesign of the FCS was accomplished to satisfy requirements 1 through 3.

Cycle 4 – A refinement of the plant model was made in order to take into account a bending mode that was neglected in the previous designs.

Cycles 1 and 3 were unsuccessful and cycles 2 and 4 produced successful flight tests.

IV-1 FIRST DESIGN CYCLE

Requirements

There were two major design requirements for this project. The first was a desire to develop a robust flight control system using QFT, and take the design through flight test. The second was a need for an inner loop FCS on Lambda that would interface with an autonomous waypoint directed autopilot.

Specifications

The time response specifications were selected base on the open-loop response of Lambda. The pitch rate was an underdamped response that settled fairly quickly. Overshoot and settling time were chosen to be *25%* and *1 sec.*, respectively, for pitch rate response. Roll rate was an overdamped response that settled quickly, and the settling time was chosen to be one second. Yaw rate was also underdamped, but it did not reach steady state as fast as the other two. Yaw rate overshoot and settling time were chosen to be *15%* and *2 secs.*, respectively. These specifications were transformed into LTI transfer functions for use in the QFT design.

Aircraft (A/C) Model

The A/C model developmental process began with the use of Digital Datcom, a computer program which predicts stability and control derivatives for aerospace vehicles based on the physical characteristics of the vehicle. Datcom information forms the baseline model of the A/C. This baseline model was refined by using system identification software to estimate the aerodynamic derivatives from actual flight test data[6]. Maximum likelihood identification was used to identify the natural frequency and damping ratios of the short period and roll modes. This information combined with the Datcom information provided a working model for the flight control system design.

FCS Design

There were two QFT designs accomplished at the Air Force Institute of Technology[7,8] (AFIT) The first was based on the DATCOM model of Lambda alone. The second design was based on the DATCOM model with the refinements made with system identification. This second design used linearized transfer functions to represent Lambda in various flight conditions, covering the entire proposed flight envelope, to accomplish the design and for linear simulations.

Linear Simulations and Nonlinear Simulations

All FCS designs were simulated using $Matrix_x$ and LTI state space models representing the full flight envelope of Lambda. After successful linear simulations, nonlinearities such as control surface travel limits were introduced into the linear simulation. A nonlinear simulation was developed at the Air Force Research Laboratory (formerly the Wright Laboratory) that incorporated a six degree of freedom simulation, automatic trim calculation, air vehicle kinematics, and control surface saturation. While this design produced the desired responses in the linear simulation, when implemented in the nonlinear simulation the original control system exhibited undesirable behavior due to the initial assumptions about allowable gain being incorrect. Thus, the allowable gain was modified to achieve a redesigned controller.

Hardware-in-the-Loop Simulation

Software from the nonlinear simulation were used to develop a hardware-in-the-loop simulation[9]. This simulation allowed the implemented FCS, which is programmed on a EPROM chip, to be tested in the A/C. When the FCS was implemented in this simulation, it was discovered that the angular rate sensors had high levels of noise, with peak values on the order of *0.5 deg/sec*. The FCS amplified this noise and this effectively masked any control command signal. The noise was recorded and was incorporated into the nonlinear simulation. The MIMO QFT CAD[1,2,5] for designing control systems allows for a rapid redesign. The noise problem was minimized by lowering the loop transmission gain and then testing the resulting FCS in the nonlinear simulation. This remedy was an "engineering decision" in order to obtain a satisfactory design. In the Third Design Cycle a more satisfactory resolution of the noise problem was achieved. Once simulations of the redesign were satisfactory, the FCS was flight tested (Flight Test #1).

Flight Test #1

Two major difficulties caused the first flight test to fail; the first was reversed polarity on an angle sensor and the second was an integrator wind-up limiter scheme that did not work. Since the inner loop FCS was to be implemented as a part of an autonomous system, turn coordination logic was implemented around the inner loop FCS that relied on the roll angle. Post flight analysis of the flight test video and data showed that the polarity of the roll angle sensor was backward, thus, when the A/C was commanded to bank, the rudder was commanded to deflect in the wrong direction. The FCS was thus turned off and the testing involving the lateral control channel was terminated. Later, during the same flight test, when the FCS pitch channel was turned on, the aircraft developed a high pitch rate. This test was also terminated and post analysis revealed that the scheme used to limit integrator wind-up had caused a numerical instability.

IV-2 SECOND DESIGN CYCLE

Requirements and Specifications and Aircraft Model

The requirements for the second design cycle did not change from the original requirements. An additional requirement was incorporated for the second design cycle that involved the design of an improved integrator wind-up limiter. The specifications and the A/C model for the second design cycle did not change from the original requirements.

FCS Design

Since the problems encountered in the first test had nothing to do with the QFT designed FCS, the same QFT FCS designed for the first flight test, was used in the second flight test. During the second flight test, there was no attempt to use a turn coordination algorithm. The insertion of an integrator wind-up limiter involved a different form of the controller implementation for the second design cycle. In this cycle instead of each of the controllers being implemented by a single software algorithm relating their respective outputs to their respective inputs, they were implemented in the manner described by E.R.12 of Chap. 9 of Ref. 1. That is, the continuous time domain transfer functions were factored into poles and zeros in order to create first order cascaded blocks (transfer functions) that were individually transformed into the discrete time domain. The individual transfer functions were then implemented, by their own respective software algorithm.. This implementation allowed limitations to be placed only on those pieces of the FCS that contained pure integrators and provided the required controller accuracy.

Linear, Nonlinear, Hardware-in-the-Loop Simulation

All simulations consisted of checking out the new implementation of the FCS. There were no problems encountered during any of these simulations.

Flight Test #2

On 20 Nov 92, the temperature was in the $60°F+$ with winds at *5* to *7 mph*. Lambda was flown in manual mode for take-off, setup, and landing. Due to problems with the first flight test the FCS was engaged only during the test maneuvers. The maneuvers performed consisted of unit step commands in all three axes. This set of maneuvers was first performed with the QFT FCS and then with the open loop A/C. As shown in Fig. 3, the QFT FCS performed as it was designed. The figure shows the responses of Lambda to a step pitch down command. The dotted lines in the plot represent the specified T_{R_l} *and* T_{R_u}. It is important to note that during this maneuver the A/C covered a large portion of its dynamics envelope by varying in forward airspeed from *75 kts* to *110 kts*.

IV-3 THIRD DESIGN CYCLE

Requirements

The requirements for the third design cycle had not changed from the original requirements. This cycle involved the design of an inner loop FCS that had intrinsic turn coordination. Also, the sensor noise problem was reduced by an order of magnitude by the addition of a hardware noise filter on the output of the sensors. It was determined that the noise originated from a motor on the sensor; the noise was a high frequency noise that was being sampled at a lower frequency. Thus, this aliased noise had a relatively high bandwidth. The remedy was to place a filter at the sensor output before the sampler. This allowed a redesign of the FCS to improve the system performance.

Specifications

For this iteration of the design a *sideslip angle command* was incorporated as part of the inner loop controller. Since Lambda has a sideslip sensor, a sideslip command was used to cause the A/C to intrinsically fly coordinated turns. That is, the goal of turn coordination is to reduce the sideslip angle to zero during a turn by using the proper amount of rudder deflection during the turn. Changing to sideslip command allowed the use of the yaw rate sensor to implement a *yaw damper* to reduced the dutch roll mode oscillations. This yaw damper was implemented by adding a washout filter, designed through the use of a root locus plot. The yaw damper was designed and then incorporated in the A/C model for a FCS design. During the second flight test the pilot felt that the aircraft's roll rate response was too slow. Therefore, the roll rate response specification was change to match that of the pitch rate. After this change the roll specifications for overshoot and settling time were *2.5%* and *1 sec*, respectively.

Aircraft Model

The sensor improvement, mentioned above, was included in the nonlinear aircraft model by recording actual noise and inserting it as a block in the model. During the system identification work for the second A/C model, some of the parameters had been scaled incorrectly. This caused some modeling errors. After the second flight test these errors were corrected through the use of system identification applied to flight test data that resulted in a refinement of the A/C model.

FCS Design

Matrix$_X$ was used to develop linearized plant models about flight conditions in the flight envelope. An attempt was made to choose flight conditions in such a way as to fully describe the flight envelope with the templates. To do this a template expansion process was developed and is explained in Sec. V.

Linear, Nonlinear, and Hardware-in-the-Loop Simulations

The refined Lambda model was implemented in all three simulations. The FCS was implemented in the cascaded method outlined previously. All simulations produced the desired responses to given stimulus.

Flight Test #3

During the third flight test, when the FCS was engaged, the A/C exhibited an uncontrolled pitching, or porpoising, behavior. While the post flight test analysis was inconclusive, a longitudinal bending mode at *13.2 rad/sec* seemed to be the likely cause.

IV-4 FOURTH DESIGN CYCLE

Requirements and Specifications

The requirements for the fourth flight test had not changed from the original requirements, but involved a refinement in the aircraft model to incorporate effects of the bending mode discovered in Flight Test #3. The specifications for the fourth design cycle were the same as those for the third cycle.

Aircraft Model

A model of the porpoising behavior encountered in the third flight test was identified by assuming that the behavior was caused by an unmodeled effect. Various models were incorporated into the nonlinear model and simulated. This simulation used the identical flight test inputs as simulation inputs and compared the simulated outputs to the flight test data. Using this procedure, see Sec. VIII, a violation of the gain margin was ruled out by increasing the inner loop gain in the model and observing the response. Instability caused by actuator rate limiting was ruled out by inserting severe rate limited actuator models in the nonlinear simulation. When a bending mode, modeled as a lightly damped pair of poles, was inserted in the model, the simulated responses were very similar to the flight test results.

FCS Design

Matrix$_X$ was used to develop linearized plant models about the given flight conditions and the FCS was redesigned based on the model containing the bending mode. Note, when the FCS from design cycle three, using the A/C model with the bending mode, there were violations of stability criteria in the frequency domain and, as expected, the porpoising behavior occurred.

Linear, Nonlinear, and Hardware-in-the-Loop Simulation

A fourth design cycle was accomplished using the new model. This design was implemented and all three simulations were run and tested. This FCS design simulation responded within specifications and, as expected, the porpoising effect was eliminated.

Flight Test #4

The fourth flight test occurred in September 1993. The field conditions were a little gusty, but within acceptable limits for the flight test. During the flight the FCS was engaged and then left engaged for the entire series of tests. The FCS performed as designed. The intrinsic turn coordination scheme worked as designed. The pilot was pleased with the handling qualities and felt comfortable flying with the FCS engaged at all times. His one criticism was that the roll rate was too slow. Since the roll rate was limited by the maximum roll rate detectable by the roll rate gyro, the problem was unavoidable. When the data was examined, it was found that all of the *60 Hz* data had been lost, but much of the *10 Hz* data had been captured. Analysis of this data showed that the FCS did cause Lambda to respond within the specified envelope, during onset of the command, but, in some cases, Lambda's response exhibited more overshoot and longer settling time than specified. These problems could be attributable to the gusty conditions, since no gust disturbance was specified during the design process. More flight testing of this FCS will be required to answer this question.

V SELECTION OF DESIGN ENVELOPE

At the onset of a QFT design, the designer must select a set of operating conditions in order to obtain the LTI transfer functions that represent the dynamical system and which are used to obtain the templates that are required for the design. The problem is which operating conditions to choose. Only those operating conditions that yield points that lie on the contour of the templates, for all frequencies of interest, are necessary. Choosing too many LTI plants may yield points that lie inside the template contours and can lead to computational problems during the design. Note by applying engineering insights it is readily determined that the template contours and not the LTI plants which lie within the template's contour determine the performance bounds that need to be satisfied by the synthesized functions. Thus, the computational workload and associated problems may be minimize by reducing the number of plants to be utilized in the design process to only those plants that lie on the template contours.

Through engineering knowledge of the problem the designer is able to determine the particular parameters that effect the operating conditions and the physical limits of these parameters. In the case of Lambda the parameters that were varied to set the operating conditions were airspeed, altitude, weight, and center of gravity. Gross limits were set for these values from knowledge of the A/C and the possible flight envelope. Next, the template expansion process was used to find the set of operating conditions that fully described the flight envelope. The template expansion process, shown in Fig. 5, is a graphical process that tracks the effect of variations of the parameters which are involved in selecting the operating conditions and determine the resulting LTI plants. The process is as follows:

1. Determine the important parameters that describe the operating condition and their minimum, maximum, and nominal values.
2. Choose a template frequency for the expansion process. This frequency should be representative of the dynamic system in the bandwidth of interest. At the end of the process, other template frequencies should be checked to insure that a complete set of operating conditions have been chosen.
3. For the template frequency of step 2, plot the dB vs phase values of the nominal operating condition.
4. On this same graph, plot the results of varying each parameter through its maximum and minimum while holding the rest of the parameters at their nominal values. This forms an initial template.
5. Identify the variations caused by each parameter. This can be accomplished by connecting the points on the template due to each parameter variation.
6. Choose the two parameters that cause the largest variations and use these to expand the template. This is accomplished by holding the remaining parameters at their nominal values and plotting the four points of the templates resulting from the extremes of the two parameters.
7. Use the outside points, on this expanded template, as nominal points for further expansion with other parameters.
8. Choose other frequencies in the bandwidth of interest to ensure that the operating envelope is completely defined.

For Lambda, a nominal flight condition was chosen to be *50 kts*, velocity, *1,000 ft* altitude, a weight of *205 lbs*, and center of gravity at *29.9%* of the mean aerodynamic cord. From this nominal trim flight condition, each parameter was varied, in steps, through maximum and minimum values, while holding the other parameters at their nominal trim values. These variations produced an initial set of templates. On these templates, the variation corresponding to each parameter was identified. Each variation when translated, on the template, identified an expanded template area of the flight envelope that required more plants for better definition.

VI CONTROL SYSTEM IMPLEMENTATION ISSUES

An implementation problem that can cause stability and performance problems is integrator wind-up. This is the situation that occurs when the controlled system cannot respond quickly enough to the commands from the controller and the commanded values keep increasing due to integrator action. A situation like this occurs when a control effector has reached its limits. The longer the system is in this state the more the commanded value increases. The problem occurs when the controller tries to reverse the command, the commanded value must be "integrated" back down to the operational range before it becomes effective. In order to prevent integrator wind-up, anti-windup algorithms must be applied to integrators during implementation. During the QFT design process the controller is in the form of transfer functions that can be of any order. For implementation, these transfer functions can be separated into first and second order transfer functions (see E.R. 12 of Chap. 9[1]). With the transfer functions separated in this manner individual integrators can be limited.

VII HARDWARE/SOFTWARE CONSIDERATION

During the modeling and development of the control system, assumptions were made as to the polarity of feedback and command signals. During implementation these assumptions must be tested. This is one of the reasons to use a hardware-in-the-loop simulation. With this type of simulation the control algorithms can be implemented and the control effectors can be monitored during simulated operation. Feedback signals can be checked by moving sensors by hand, if possible.

The other phenomena that a hardware-in-the-loop simulation can identify is the effects of feedback noise on the controlled system. If the feedback noise is within the bandwidth of the control system, and the noise has not been included in the modeling or simulation, the controller may need to be redesigned to account for the noise. This might result in a trade off between performance and noise rejection. Sometimes it is possible to implement a hardware filter after the sensor, but before the sampler too reduce the noise in the bandwidth of interest.

VIII BENDING MODES

During the design of a control system, the effects of higher frequency modes on stability and performance must be considered. In A/C, one source of higher frequency modes is structural bending. A control system that excites a bending mode in a flying A/C can produce disastrous consequences. During the modeling process it is very important to include the effects of these higher frequency modes so they can be minimized during the design process. In the case of Lambda, the existence of a bending mode was discovered during a flight test.

VIII-1 Lambda Bending Example

Following the initial flights, the A/C operators decided that they would prefer a different feedback structure in the FCS that included turn compensation. Thus, to implement turn compensation, a sideslip angle command was incorporated as part of the inner loop controller. The goal of turn coordination is to reduce the amount of sideslip angle during a turn by using the proper amount of rudder deflection during the turn. Since Lambda has a sideslip sensor, sideslip feedback was used to cause the A/C to intrinsically fly coordinated turns. Changing to sideslip command also allowed the use of the yaw rate sensor to implement a yaw damper to reduced the dutch roll mode oscillations. This yaw damper was implemented by adding a washout filter, designed through the use of a root locus plot. The yaw damper was designed and then incorporated in the A/C model for a FCS design.

When this design was finally flight tested, a porpoising behavior was observed. To ensure flight safety, Lambda was flown to a safe altitude by the pilot before the QFT FCS was engaged. The pilot had Lambda flying in level flight when the longitudinal portion of the QFT FCS was engaged. At this point Lambda began oscillations in the pitch axis and the QFT FCS was disengaged immediately. In order to collect sensor data on this behavior, Lambda was flown back to level flight, the longitudinal portion of the QFT FCS was engaged and the sensor data was recorded for further analysis. Pitch attitude data from this flight is shown in Fig. 5 whose high resolution data was at a 60Hz sample rate.

VIII-2 Unmodeled Behavior

A model of the porpoising behavior was identified by assuming that the behavior was caused by an unmodeled effect. Various proposed models were incorporated into a nonlinear model of Lambda and simulated. This simulation used the actual flight test inputs as simulation inputs and compared the simulated outputs to the flight test data. Using this procedure, a violation of the gain margin was ruled out by increasing the inner loop gain in the model and observing the response. Instability caused by actuator rate limiting was ruled out by inserting severe rate limited actuator models in the nonlinear simulation. Upon reviewing the video record of the flight, it was suggested that the A/C appeared to have a second-order bending mode in the longitudinal axis. It was possible to excite and observe such a mode by tapping rhythmically on the tail of the A/C.

A bending mode modeled as a lightly damped pair of poles at *13.2 rad/sec*, just within the bandwidth of the FCS, was inserted in the nonlinear simulation as shown in Fig. 6. This model generated a pitch acceleration signal from elevator deflection which was passed through the second order filter:

$$\dot{q} = \frac{-20}{s^2 + 5.28s + 174.2}\delta_{elev}$$

The simulated response was very similar to the flight test results. $Matrix_X$ was used subsequently to develop new linearized plant models containing the bending mode about the given flight conditions. The Bode plots of these models are shown in Fig. 7

The new plant models were entered in to the MIMO QFT CAD software. The FCS was redesigned based on the new models using the FCS from the previous design cycle as a baseline. The previous controller was:

$$g_{11}(s) = \frac{1093(s+8.5)(s+11)(s+3.9 \pm j2)}{s(s+2)(s+80)(s+36 \pm j48)}$$

The MIMO QFT CAD software showed that, with the old controllers, there were violations of the stability criteria on the Nichols chart.

The standard method of design would be to add a notch filter to keep the mode from becoming excited. The bending mode is close enough in frequency to the performance bandwidth of Lambda that care needs to be taken to design a controller that will be able to take advantage of the available bandwidth to deliver performance, stability, and disturbance rejection without exciting the bending mode. A standard notch filter would not take advantage of any beneficial dynamics at frequencies nearv the bending mode. It would also increase the order of the compensator. As an alternative, the inner loop filter was revised to compensate for the new information. It was also possible to design a fourth-order controller to replace the earlier fifth-order design, lowering the complexity of the controller instead of increasing it. The new controller was determined to be .

$$g_{11}(s) = \frac{125(s+1)(s+2.5 \pm j9.4)}{s(s+10)(s+35 \pm j35.7)}$$

A characteristic of a bilinear transformation is that, in general, it transforms an unequal-order transfer function ($n_s \neq w_s$) in the s-domain into one for which the order of the numerator is equal to the order of its denominator ($n_z = w_z$) in the z-domain. This characteristic must be kept in mind when synthesizing $g_i(s)$and $f_{ii}(s)$. Therefore, a nondominating s-domain zero at -150 is inserted in g_{11}.

With the MIMOQCAD program it was possible to shape the loop so that at *5 rad/sec* the loop intersected a point on the Nichols chart where the stability boundary and the performance boundary met. This was an optimal point for the loop to pass through given Lambda's performance bandwidth. The new A/C model was implemented in the nonlinear simulations and tested with both controllers. As expected, the resonance occurred with the FCS that was designed in Design Cycle #3. The FCS resulting from Design Cycle #4 responded within specifications. The new FCS passed a hardware-in-the-loop simulation and was scheduled for a flight test. During the next flight test, the field conditions were gusty, but within acceptable limits for the experiment. The QFT FCS was engaged and there was no noticeable oscillation. The pilot was very pleased with the handling qualities and felt comfortable flying with the FCS engaged for the entire series of tests. The only problems encountered were some roll performance problems which could be attributed to the windy conditions. Pitch response during this flight is shown in Fig. 8. Unfortunately, the test data recording function failed during the flight so that the only data available is low resolution data ($\pm 0.5°$) recorded at *10Hz*.

IX SUMMARY

Control design and implementation in the real world is an iterative process. Initial steps are performed with linear models that have been formulated with simplifying assumptions. After successful testing of the designed control system, based upon these simplified models, it is tested on increasingly realistic (nonlinear) models. At any point in the design process, if the control system does not meet performance and stability specifications, the control system must be redesigned and retested on the simplified models. This redesign is followed, once again, by testing on the nonlinear model (see Fig. 1). At every point of the design process the designer must be aware of test assumptions so engineering judgement can be use to help guide the design to a successful implementation and operation. The bottom line is that the controlled system must meet the requirements set out at the beginning of the process.

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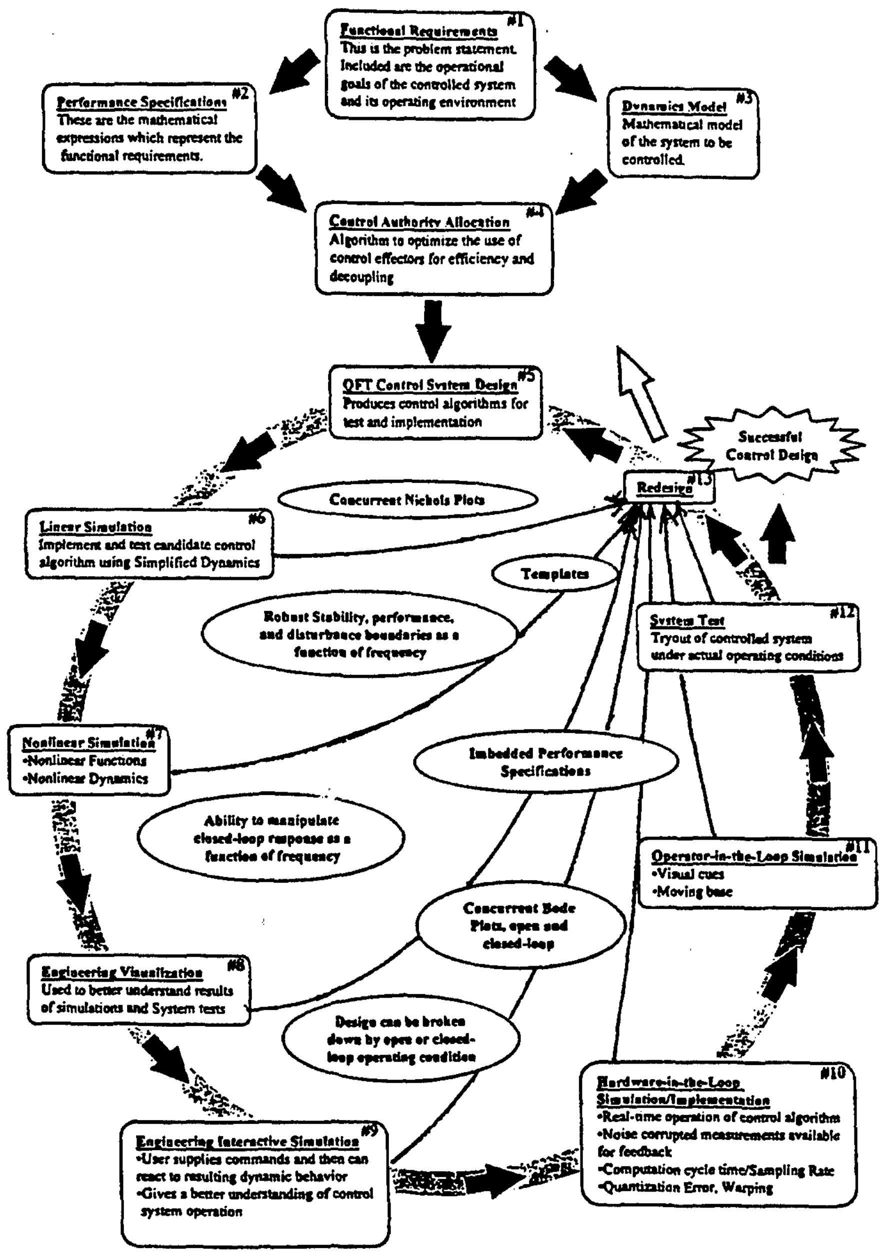

Fig. 1 The QFT c.ntrol system design process: Bridging the Gap.

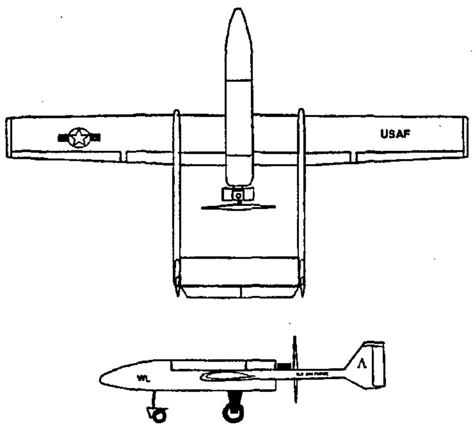

Fig. 2 Lambda Unmanned Research Vehicle (URV).

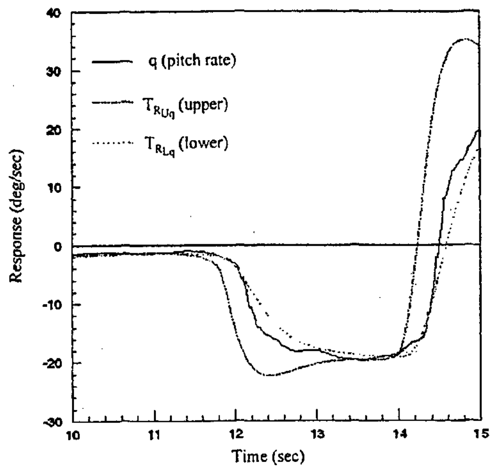

Fig. 3 Response to pitch-down command.

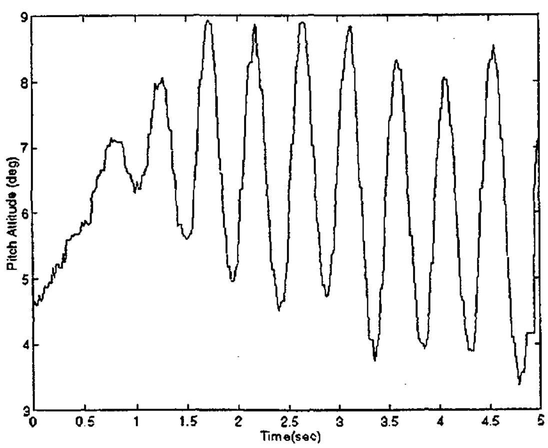

Fig. 4. Pitch resonance during flight.

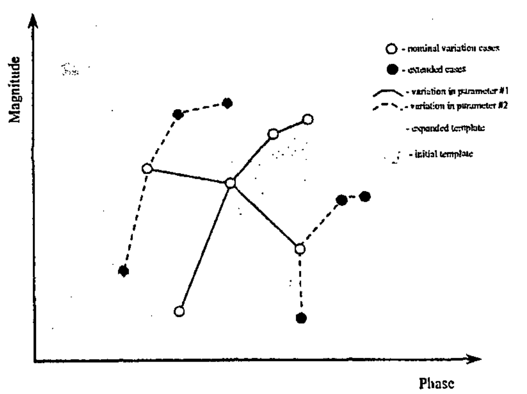

Fig. 5. Template expansion process.

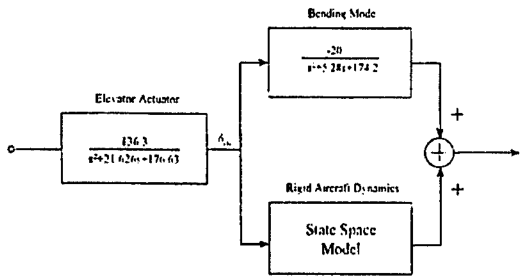

Fig. 6. Lambda bending model structure.

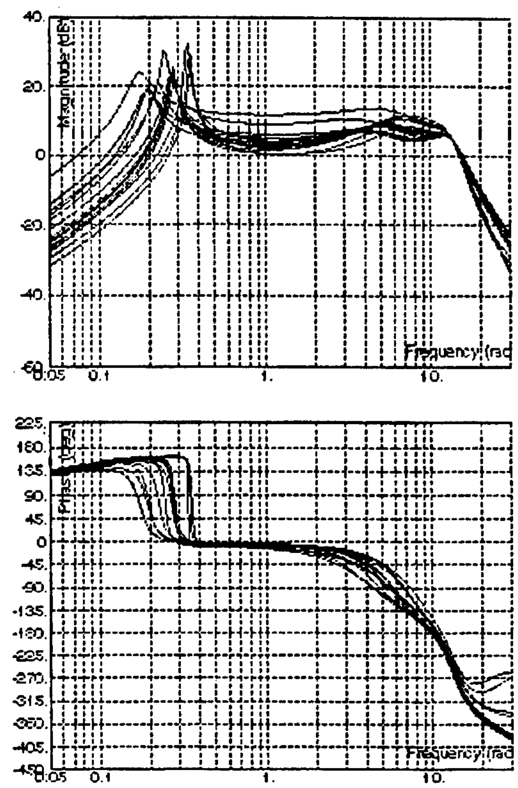

Fig. 7 Lambda bending models.

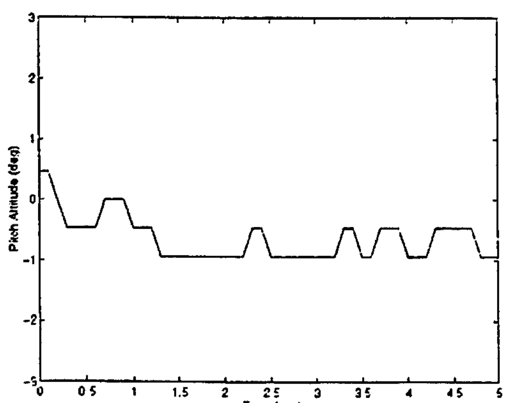

Fig. 8. Pitch attitude during flight.

CRECUS : A Radar Sensor for Battlefield Surveillance UAVs

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Summary

The paper describes a SAR/MTI radar sensor for Air-to-Ground Surveillance UAVs designed as a slow-flying, medium-altitude UAV payload. We present experimental results and emphasize salient conclusions obtained following the developmental flight test phase.

1. Introduction

CRESUS, an acronym for " Charge Radar Embarquée Sur UAV de Surveillance " (" a radar payload for surveillance UAVs ") is a radar designed by THOMSON-CSF and sponsored by French MOD (DGA). This radar is dedicated to the SAR/MTI Air-Ground Surveillance Operations of French Army.

The radar is fitted for low velocity UAVs such as BREVEL, CRECERELLE, SPERWER. CRESUS is also a potential demonstrator for a future operational radar to be carried on light Medium Altitude Long Endurance UAVs (MALE).

A radar demonstrator, partially including UAV integration design considerations, has been realized and flight-tested aboard a helicopter.

Section 2 of this paper focuses on operational concepts, mainly on all-weather capability for permanent surveillance missions. Section 3 gives physical and functional description of the radar, followed by the bimodal characterization of the sensor (MTI and SAR) while Section 4 considers the implemented MTI and SAR signal processing. The main goal of these two sections is to give some insights about the constraints faced by the radar payload designer with respect to the UAV context, an important constraint being the angular accelerations of the platform. Section 5 discusses the flight testing procedure performed in 1998 and presents experimental results illustrating potential radar capabilities. Section 6 concludes with some possible future developments for this type of radar.

2. Operational requirement

The main operational concept of the system is founded on all-weather capability to collect intelligence on a battlefield divisional zone. Intelligence concerns progression and deployment of friendly or hostile units. The sensor must be able to detect and localize :

- Static targets that can be recognized by their typical deployment (ground command centers, batteries of surface-to-air or surface-to-surface missiles, non-moving columns of vehicles, logistics bases, etc.)
- Mobile surface vehicles (light or heavy vehicles, wheeled armoured vehicles or tanks)
- Moving or hovering helicopters.

In case of a mission plan inside the hostile territory, the surveillance system may be a complement of a standoff system (such as the HORIZON system whose the radar is developed by THOMSON-CSF) because distant observed areas may be masked by the geographical relief. In standoff conditions, the system is able to perform a permanent surveillance mission near borders or near the FEBA (characterized by fast variable threats with short-time effects).

These particular contexts led us to choose a medium range radar sensor. Compared with short range, medium range offers several advantages :

- a widely increased surveillance capability in terms of size of observable area,
- a reduced vulnerability as surveillance mission is performed at medium-high altitude without having to fly over the potentially heavily defended areas to be observed , and allowing to be safe from line-of-sight EO weapon systems by remaining hidden behind clouds,

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

- simplified operational use with respect to mission preparation and flight plan,
- a secondary standoff surveillance capability for control of borders.

A radar sensor is more suitable in medium range than electro-optical systems (visible or infrared spectrum) due to the intrinsic radar features :

- robustness to weather conditions, with the particular low sensitivity to the presence of clouds along the line of sight, whereas electro-optical systems installed on UAVs are inefficient in such conditions,
- as a direct consequence, the ability to observe from higher altitudes and longer ranges than electro-optical systems.

Furthermore, a medium range radar is an adequate payload for a light UAV.

3. Main features

The main features and performances of CRESUS are presented in the following sections.

3.1 Radiofrequency features

CRESUS operates in Ku-band, which is a good trade-off for effectiveness at medium range. Benefits of Ku-band compared with a lower band are mainly :

- easier integration due to the corresponding technology,
- for a given antenna size, better detection of slow target in MTI mode than a lower band
- for a given azimuth resolution, shorter integration time and tolerance in residual accelerations in SAR mode.

The main drawback of the Ku-band is the propagation loss due to water in the atmosphere (rain, fog, and clouds). This is a limit with respect to the range of the radar. This restriction has to be taken into account through the radar design phase.

The bandwidth of the CRESUS radar is 1 GHz-class and peak radar transmitted power is 100 W-class.

3.2 Range and swath

As seen above, CRESUS is medium range. The MTI swath is 10 km-class and the SAR swath is 3 km-class, these ranges being enough to procure an adequate mission plan.

3.3 Resolution and accuracy

For the MTI mode, the velocity extent is compatible of helicopter flight, velocity resolution is 1 km/h-class, distance resolution is 10 m-class, and localization accuracy is 100 m-class.

For the SAR mode, both resolutions in distance and azimuth are metric-class, this being adequate for cartography and detection of fixed targets.

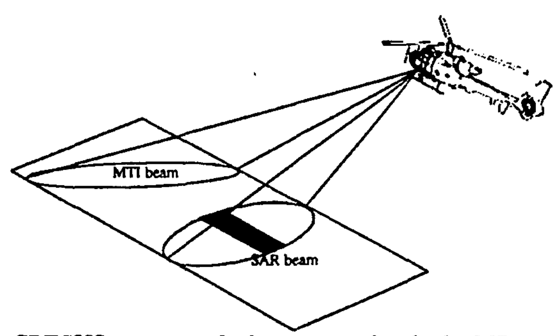
3.4 Antenna

A side-looking antenna has been selected. The main advantages are :

- high range and swath performances due to larger antenna size,
- in MTI mode, good detection performances of slow targets without complex processing,
- conformal antenna making easier integration on different carriers.

The SAR line of sight is orthogonal to the UAV longitudinal axis, providing a minimum integration time. The MTI line of sight is slightly tilted with respect to the UAV longitudinal axis , thus providing a surveillance capability when mission plan is along roads and an early alert for SAR surveillance of very active areas.

Next Figure shows areas simultaneously illuminated by the radar.



CRESUS uses a dual antenna for both MTI and SAR modes.

Vertical beamwidth is large enough to take into account roll and pitch motion of the UAV. Horizontal beamwidth in SAR mode is large enough to take into account yaw motion of the UAV during integration time. This is adequate for medium range because of the important integration gain of that mode.

Horizontal beamwidth of the MTI mode is thin enough to achieve the specified range and to detect targets having a low velocity. Target illumination time is kept constant since the antenna is steered in the horizontal direction, this being performed by a bearing scattering antenna combined with frequency hoping.

3.5 Modes management

MTI and SAR modes are temporally interlaced. Interlacing allows the ground surface to be continuously scanned in both modes with the same effectiveness for each mode as if it were operating alone.

3.6 Physical architecture

The CRESUS demonstrator is decomposed in three subsets. The first subset is a pod mounted on a Gazelle helicopter for flight-testing. It was fixed on the arm usually dedicated to Hot missiles.

The second subset is an operation bay standing inside the Gazelle.

The third subset is the ground segment.

The pod includes : TOP emitter, reception chain, SAR pre-processing, power-supply, aerial composed by MTI antenna and SAR antenna and the gyrometer / accelerometer equipment. In order to be autonomous with regard to the platform, CRESUS radar is actually equipped with its own motion sensors.

The operation bay embodies a on-board monitor, a computer and a processing unit. The processing unit implements control of the radar and real-time MTI processing. In addition, it includes the GPS system. Board monitor and board computer are useful only for the demonstrator.

The ground segment is composed by two UNIX workstations : a HP 9000 J200 and a SUN Ultra 1. SAR processing is implemented on the HP workstation whereas operating is implemented on the SUN workstation and the man-machine interface displayed on a 19" high-resolution color monitor.

3.7 Specific features for the demonstrator

Several modifications have been adopted in order to reduce the cost of the demonstrator. However, these modifications should not affect the conclusions drawn from flight testing as they are related to features mastered by Thomson-CSF Detexis for a long time.

Platform: The platform chosen is a French Army Gazelle helicopter, presenting speed and flight level capacities very close to those of a potential UAV vehicle.

Antennas: In order to simplify the design, the dual antenna foreseen in case of a drone is replaced by two different antennas dedicated to each one of the modes (SAR and MTI). However, the two antennas are tighten together and cannot be pointed independently.

Data Link : There is no real-time data link transmission. Raw data is stored on-board on a removable hard disk, with a 4 Mbits/s rate, identical to the one specified for the final payload .

SAR swath : In order to reduce the computation load, the size of the swath has been reduced by a factor of four.

Size : The target mass (20 kg) and volume (25 l) for the radio-frequency part of the payload have not been modified.

4. Data processing

The data processing for the CRESUS payload derives from the Thomson-CSF/Detexis expertise in SAR and MTI, obtained along the development of systems such as HORIZON and RAPHAEL.

In order to comply with the requirement of 4 Mbits/s in terms of throughput, the selected architecture is described hereunder :

- On board MTI real-time processing,
- On board SAR raw data pre-processing,
- Imaging processing performed off-line in the ground segment.

Data acquired during flight test are processed on ground within commercial off-the-shelves (COTS) workstations.

4.1 MTI signal processing

On-board MTI real-time processing includes :

- Set-off to platform motion,
- Detection and removal of ambiguity for moving targets (surface vehicles and helicopters),
- Specific detection processing for hovering helicopters,
- Accurate target localization using radar data and motions sensor data.

Platform motions have a direct impact to the location of clutter in the range-Doppler map. Clutter echoes form a curved strip, with precise shape related to the vertical and horizontal directions of the beam, therefore depending of platform motion. An adaptive compensation of these motions has been implemented in order to cancel the Doppler relation of clutter with these motions. This allows a correct filtering of the stationary echoes and an improvement of the velocity measurement of mobile echoes.

4.2 SAR signal processing

The SAR computation algorithm is made up of a pre-processing function performed on-board in real time and of an image production and display functions performed off-line in a ground segment.

The pre-processing function (filtering and under-sampling) is meant to reduce raw data throughput.

The other data processing functions (written in C) are running on a workstation.

Software is modular in order to get the following advantages :

- Capability to select all software components for complete processing refinement or only a subset of the available components to speed up the computation process,
- Capability of adding new features and/or capability of upgrading the existing software items in a quick and efficient way.

The main features already available are :

- Analysis and correction of raw data
- Motion compensation based on strapdown inertial accelerometers/gyro and GPS information
- Doppler centroid computation
- Correction of phase errors
- Autofocus
- Imaging
- Data re-sampling in both range and azimuth with a constant pixel size
- Display and specific tools such as target detection functionality

Some other software functions can be activated, such as multi-look or radiometric corrections due to antenna angular motions during data acquisition.

Average computation time when activating all software components listed above is around 3 minutes.

The most difficult part of this algorithm is linked to the determination of the antenna motion errors. As indicated, the platform used during the experiments is a light platform (Gazelle helicopter). Depending on flight conditions, the angular and linear motions can cause various types of image degradations including of course defocusing.

Furthermore, due to the deliberate choice of low-price motion sensors, the low frequency errors (including bias due to the initial antenna positioning angular error) had to be corrected by an autofocus technique.

4.3 Ground segment

The display of both MTI and SAR processing results can be performed within the ground segment facility.

Two main displays are available to the operator.

The first one is the general display featuring :

- A ground map presenting :
  - ❑ SAR and MTI swaths
  - ❑ MTI detected targets (closing-in and moving-away targets, hovering helicopters) with their characteristics (position, speed, RCS)
- a browse SAR image adequate for selection of images of interest by the operator

The second display is a full scale SAR display with access to several analysis tools such as thresholds tuning and target detection capabilities (CFAR detection).

5. Experimental results

5.1 Organizational considerations

A number of flight tests were conducted in an environment close to an operational one although using the Gazelle platform.

These flight tests were useful for assessment of the expected technical performances of the radar. In addition a significant collection of data has been stored for further evaluation of the radar over various conditions : nature of ground, altitude, distance (and hence elevation angle of sight), etc.

Technical flights have been conducted at first, the objective being to verify the actual performances of the radar : range, localization accuracy, ground range resolution, minimum required target velocity for the MTI mode; resolution, image quality (PSLR, ISLR), geometric conformity for the SAR mode.

Mobile targets were precisely and continuously localized using a Differential GPS Positioning System. These targets were moving with different velocity vectors, aspect angles and inter-distances.

Fixed targets consisted in a set of scattering trihedrals distributed on ground according to a characteristic pattern.

In a second time, virtually operational flights have been carried out, in order to evaluate the ability of the radar to detect vehicles moving in column as well as realistic fixed targets, in an environment close to an operational one.

There have been 24 trial flights with a total of 30 hours.

Preparation of flight was quite rudimentary and easy. It consisted to define the suitable helicopter trajectory for observation of surface targets and then to program the effective SAR and MTI swaths.

Aircrew consisted in three-person from the French MOD (center of flight testing, CEV of DGA) : the pilot, the co-pilot and the operator in charge of control of the MTI detection through the on-board display.

During flight, a radio communication link was used to coordinate surface targets and flight test vehicle to insure the presence of moving targets during CRESUS use in the area of interest.

5.2 General assessment

No failures have occurred during the whole experimental campaign. Use of the radar has proved to be easy and flexible enough to ensure success for each flight, even in the occurrence of heavy winds.

In case of wind, helicopter trajectory was corrected in real time according to information on the in-board display, and radar swath was easily adapted in order to recover the targets .

An awkward experience that could be noticed has been the occurrence of angular skips of the MTI beamforming (a few degrees forward or backward, with a mean rate of one per minute).

An antenna skip might happen just at the moment that the beam was illuminating a target. In case of forward skipping, target was not detected; in case of backward skipping, target was detected twice.

Angular motions of the platform are the origin of this observation. Normally the antenna is steered along a commanded azimuth. However, when platform angular motion is too large, the radar beam is commanded to an intermediate bearing, this being the cause of the steered antenna skip.

Antenna skipping does not exist for the SAR mode because SAR antenna is not steered.

5.3 MTI experimental results

Based on the experimental results, the radar effectiveness has been proved to be compliant with the specified requirements. Particularly, the relative (with respect to the platform) localization accuracy is excellent. However despite this fact, some targets may be localized alongside the roads. That happens if inaccurate data relating to the platform position and angular motion (resulting in azimuth inaccuracy) are used.

Image 1 illustrates the MTI detection as delivered by the ground segment. This is an urban area. A great number of vehicles may be seen along the highways (and particularly on the motorways) and it seems very difficult to discern each vehicle.

False targets have been observed due to residual signals reflected by the terrain after filtering of clutter energy. These false targets are not very numerous for agricultural region and they are nearly eliminated for mountainous region with sparse vegetation.

Images 2 and 3 show other typical MTI mapping results (several targets moving on a mountain road).

Image 1

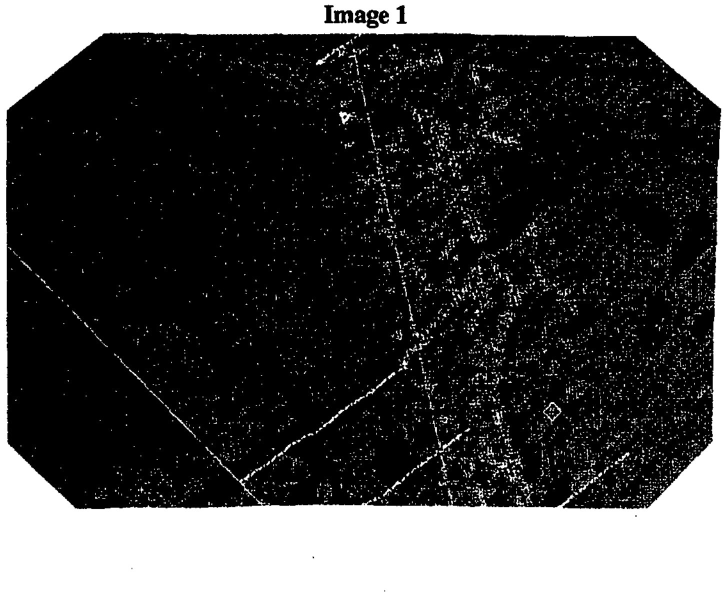


Image 2

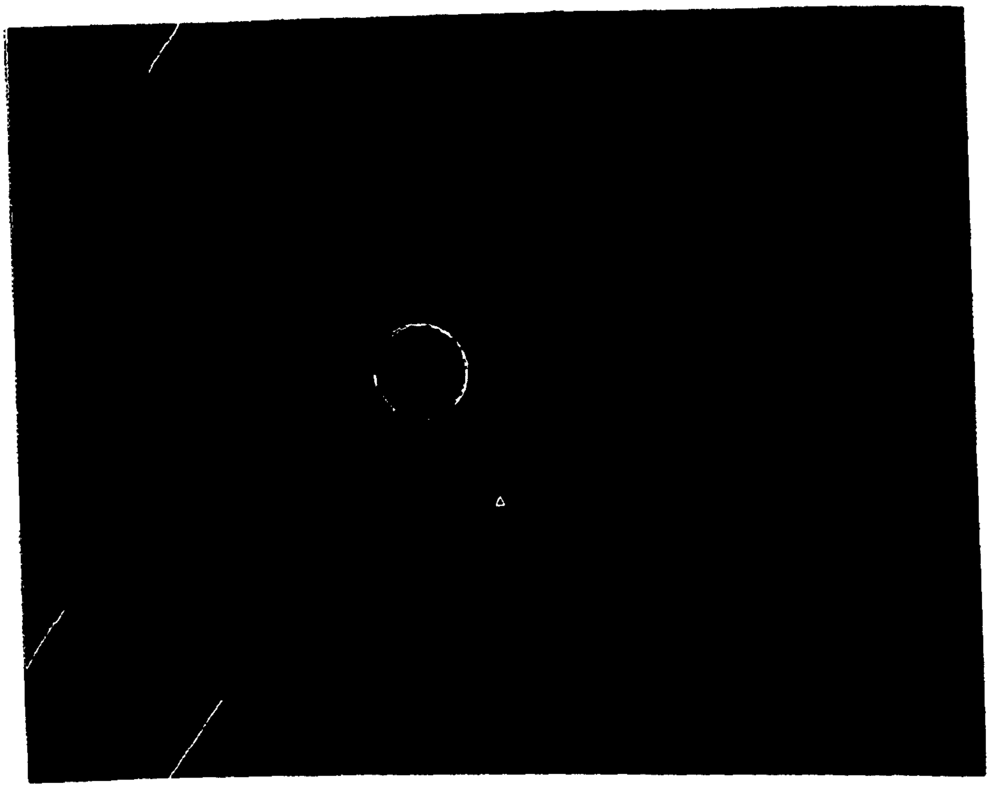
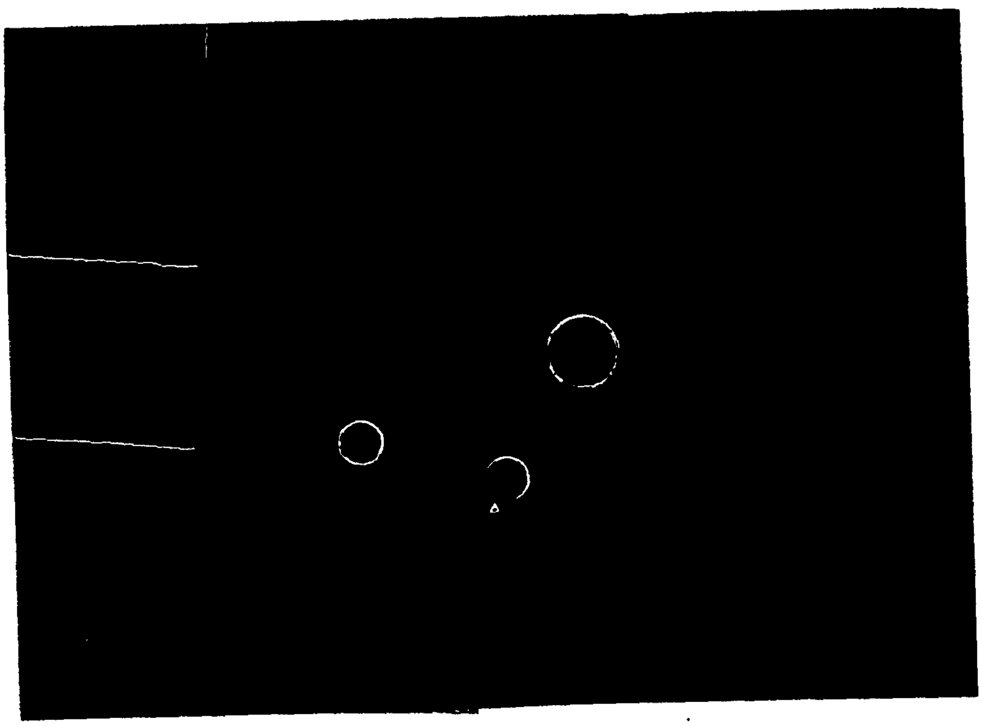


Image 3



5.4 SAR experimental results

All the measurements performed on collected data concluded to the good quality of the SAR sensor in full accordance with the specified requirements.

In particular, the use of gyro and accelerometer data along with an autofocus technique allowed a complete and satisfactory spurious motion error compensation.

Image 4 hereunder shows a typical imaging result (single look image with scatterers evenly spaced on an airport).

An extra functionality, which has been investigated, is the multi-look capability without loss of resolution.

In fact, the interlacing of SAR and MTI modes implies that the SAR mode is a burst mode. However, due to the small amount of time between two SAR data acquisition, to the low platform speed, and to the relatively wide antenna azimuth aperture, two successive SAR images greatly overlap. Because of that and with a correlation and re-sampling process between the overlapping images (which causes a greater computation time compared to the single look process) it is possible to reduce the speckle effect while still having nominal range and azimuth resolution for the SAR images.

Image 5 hereunder (airport) illustrates this functionality.

A moving target is clearly visible in the upper part of the picture.

The following pictures show different backgrounds :

- Image 6 (lake, fields, urban areas)
- Image 7 (hills, no target on the road)
- Image 8 (hills, 4 targets on the road)

6. Conclusion

Flight test results of the CRESUS bimodal SAR/MTI radar have proven the surveillance capability of that sensor from a low velocity, medium altitude platform such as the BREVEL, CRECERELLE or SPERWER UAVs.

Our observations on the MTI steering antenna behaviour when carried on a rather unsteady platform are a useful guidance for solutions (hardware and software) of the antenna skip problem.

The next step in the evolution of the radar is the implementation of a very high resolution SAR mode (sub-metric class). Simulation work is now under way at THOMSON-CSF. The simulation generates raw data representative of the different subsets of the radar and uses the actual ground segment SAR algorithms. Implementation of high resolution SAR mode requires a minimum change of the hardware since the evolution was anticipated at the beginning.

For a future operational radar, range performance of the radar has to be improved, therefore leading to both a larger antenna and an increased emission power.

After such improvements in resolution and range, CRESUS will have operational performances adequate to light MALE UAVs.

Image 4

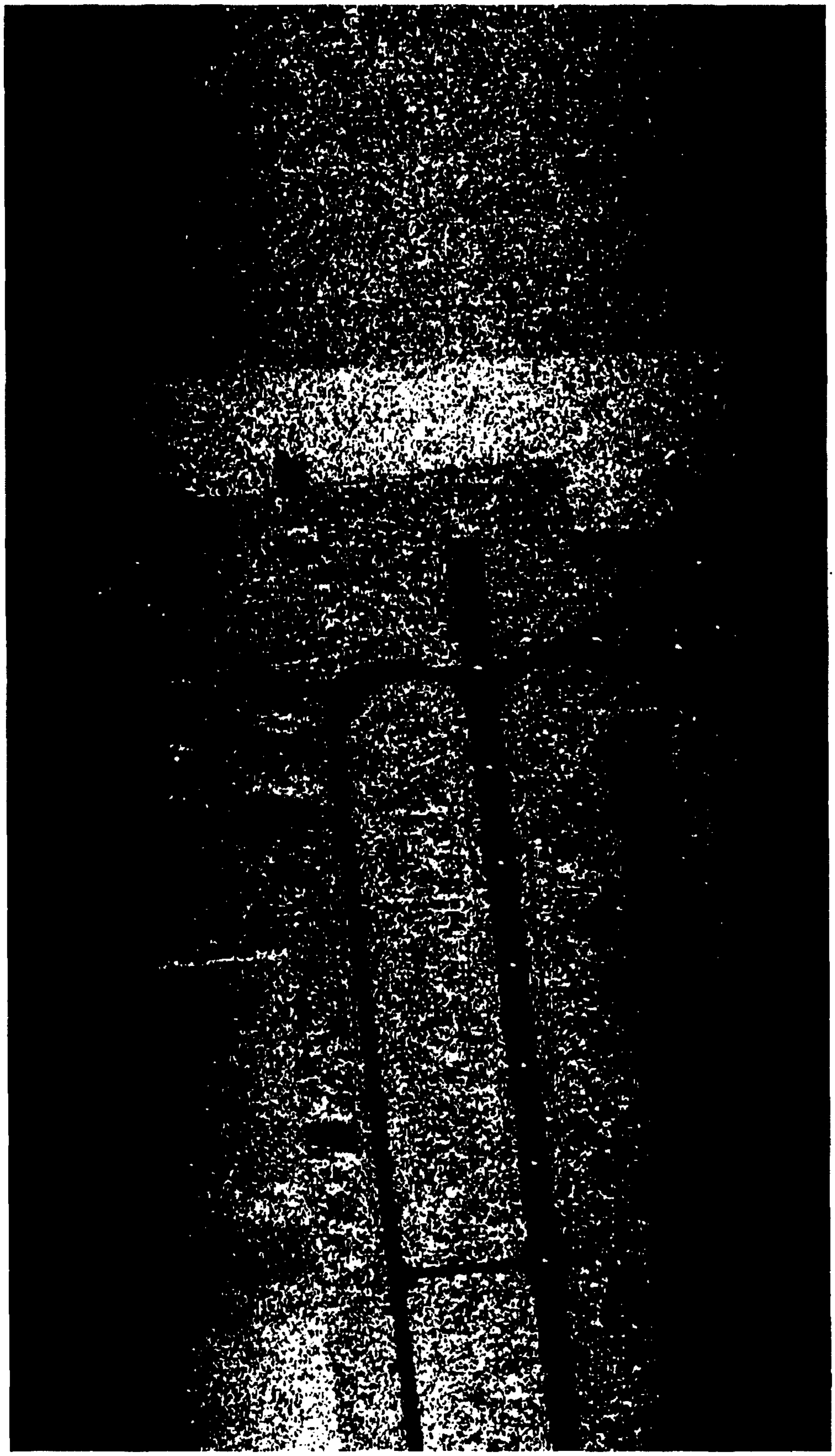


Image 5

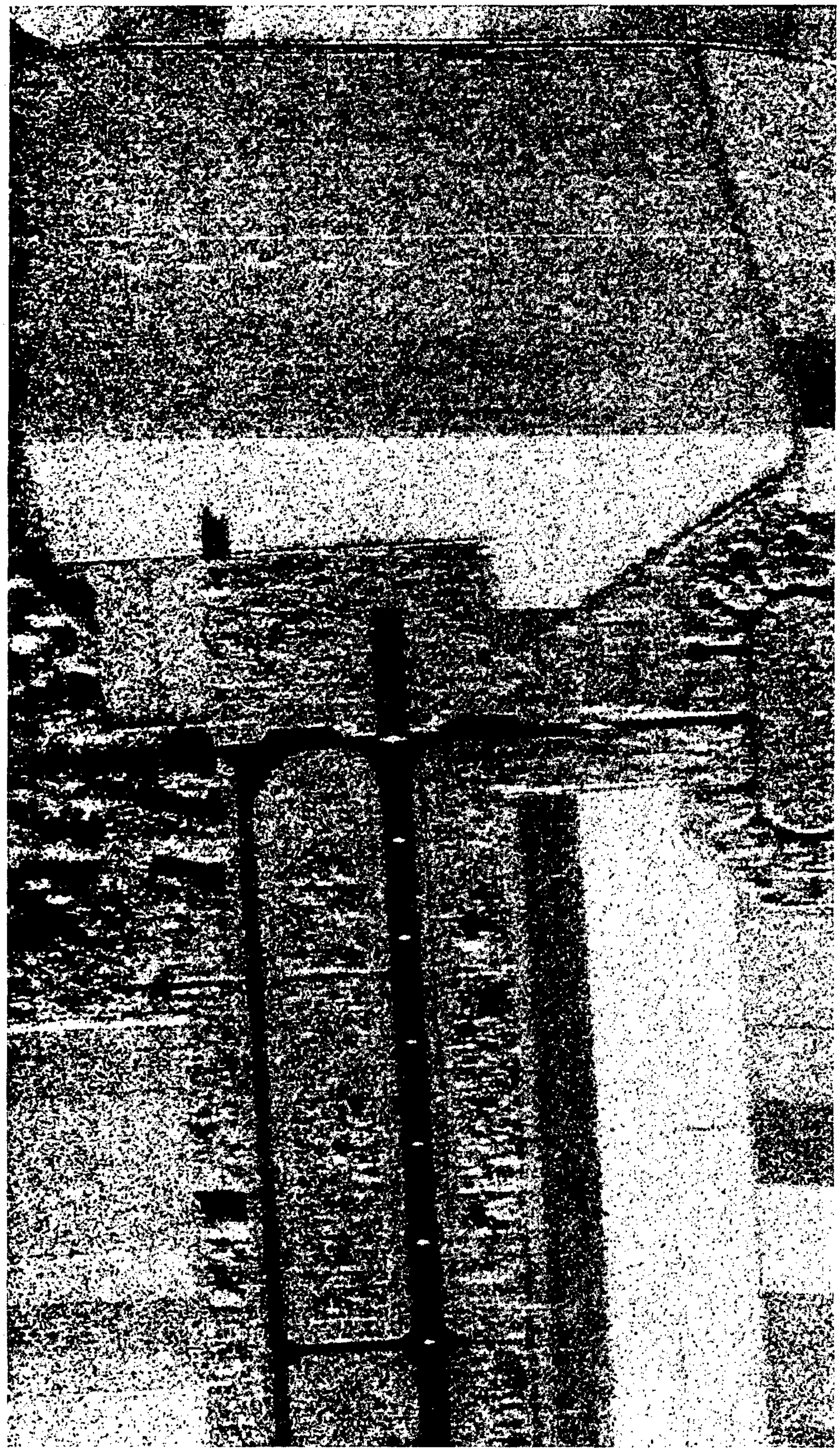


Image 6

Image 7

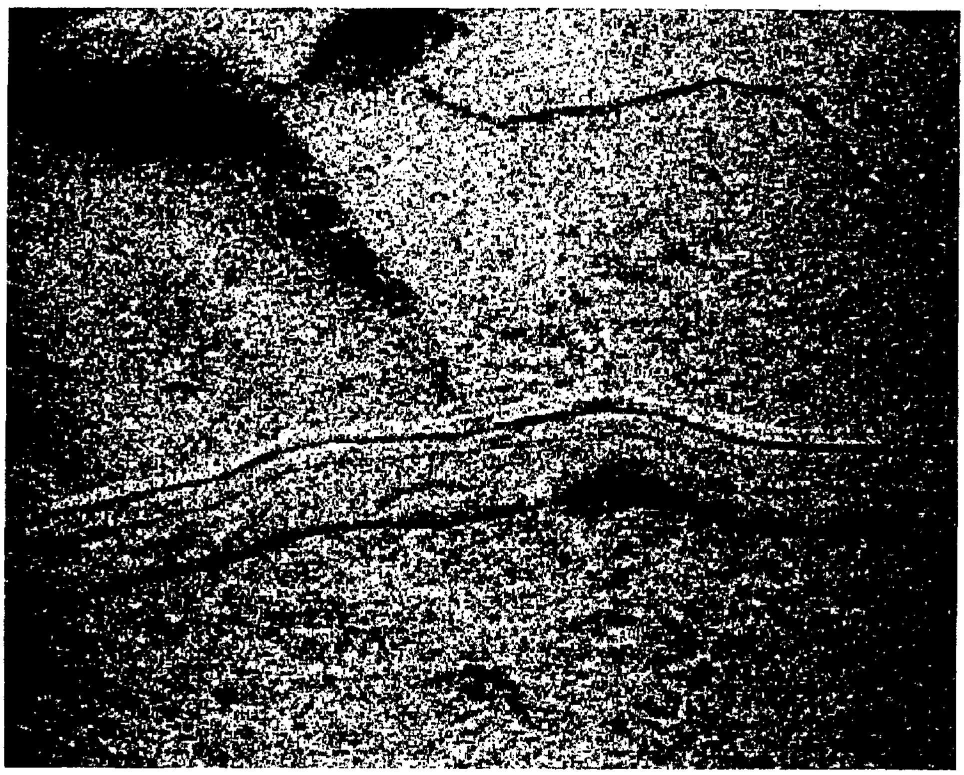
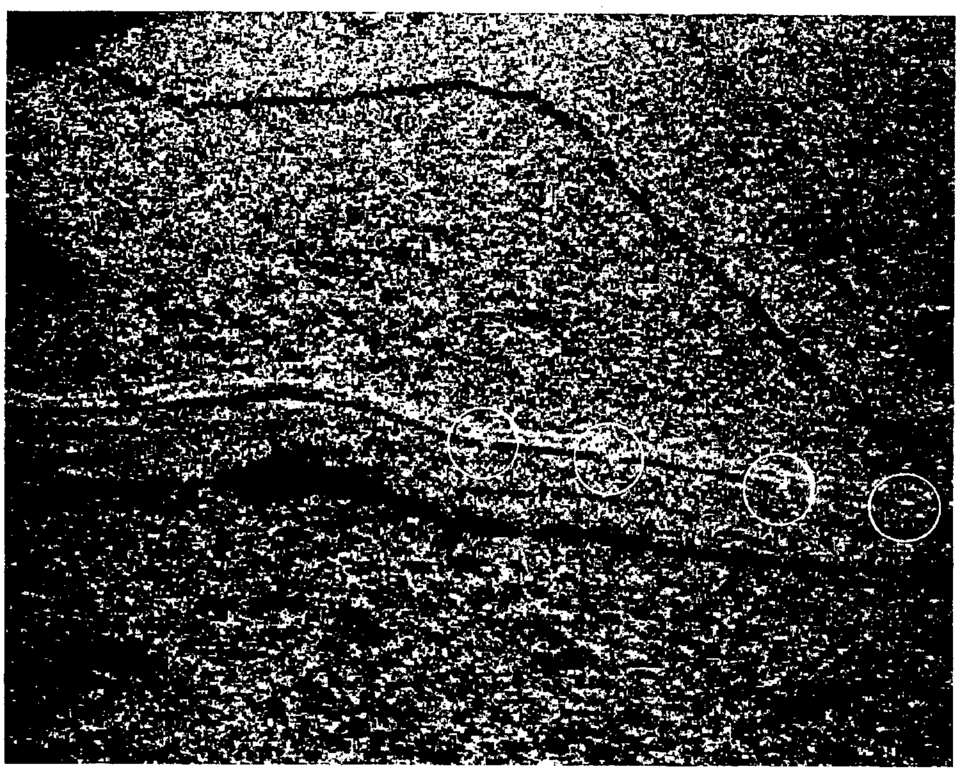


Image 8



Unmanned Air Vehicles for the Army - Future Concepts

(Ankara 26 - 28 April 1999)

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Sebaldsbrücker Heerstr. 235
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The lecture comprises the following contents:

0. Preface

The micro drones are not considered in this report because the required technologies and special branches have to be applicated with partly completely new attemps and approaches. As examples for this statement I will mention only the aerodynamics, the microelectronics and micromechanics as well as bio-chemical sensors and neuronal intelligent structures.

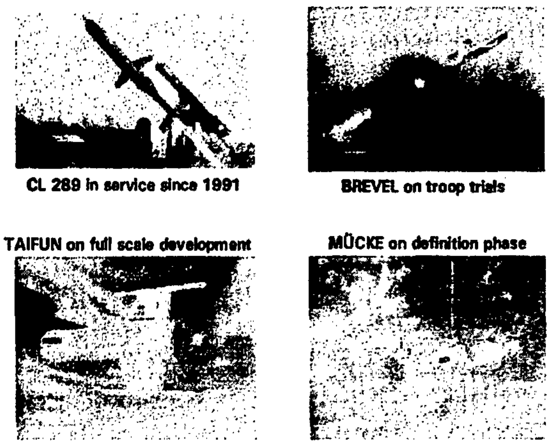
The way shown here to future UAV systems goes ahead from of the existing and in near future developed technologies for tactical UAV systems and demontrates about application variants the direction towards far-reaching UAV systems with NATO compatibility.

1. Starting Position

1.1 UAV Systems of the German Army

Since the introduction of the reconnaissance drone CL 289 in 1970 the German Army collected more than 25 years experience with reconnaissance drones.

The intensive and knowledge based concern with UAV technologies has led to this, that drones will also be set into operation for combat and jamming support by the German army.
The drone system CL 289 for real time tactical reconnaissance is up to 75 km penetration depth in operational



CL 289 in service since 1991 — BREVEL on troop trials — TAIFUN on full scale development — MÜCKE on definition phase

Fig. 1-1: UAV Systems of the German Army

use. In the following report we will learn about the peacekeeping missions of the CL 289 in Bosnia.

The drone system BREVEL is now under test in troop trials and is put into service in 2001.

The combat drone of the German Army TAIFUN will be put into service in 2005, the development started in mid 1997. With this weapon system the army attains for the first time the ability for operative combat in the depth.

The jamming drone MÜCKE is tested during the defination phase with prototypes in flight trials on the basis of the BREVEL system. The introduction into service is planned for the year 2004.

The drohne systems BREVEL, TAIFUN and MÜCKE will be realized under the responsibility of STN ATLAS Elektronik GmbH, Bremen.

I like to introduce these three systems to you briefly.

1.2 BREVEL: Target Reconnaissance and Target Localization

The drohne system BREVEL will be used by the artillery for acurate target localization, post strike reconnaissance and for the extraction of information of the operational situation.

The information are obtained by means of a stabilized, ground controlled infrared onboard camera and are sent in real time via a jam resistant data link to the ground

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

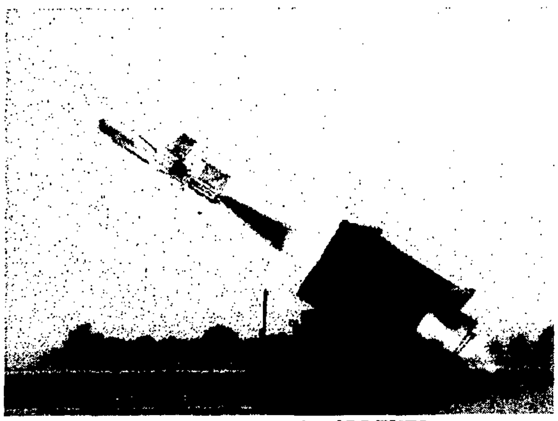


Fig.1-2: Booster Launch of BREVEL

control station. The flight profiles for each mission are preplanned in the ground control station and can be changed during flight at any time.

A BREVEL system includes:

- 10 air vehicles
- 2 launch vehicles
- 2 ground control stations
- 2 antenna vehicles
- 2 maintenance vehicles
- 2 recovery vehicles

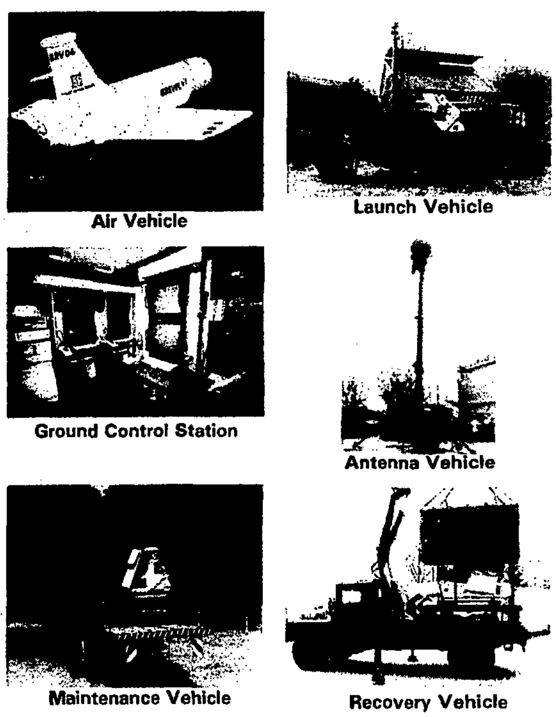


Fig.1-3: System Elements of BREVEL

The tailless configuration of the BREVEL drone has particularly proved itself at extreme wind conditions.

The air frame is produced in a material compound structure with radar energy absorbing features and also in an infrared, acoustic and visual signature reduction manner, which was developed by STN ATLAS. After having received the mission order the drones have to be launched rapidly and without restrictions for the launch direction. Therefore the launch is carried out with a booster from the launch vehicle.

The ground control station has 3 work stations for mission planning, mission guidance and control and sensor image evaluation.
The data link antenna at the ground can be seperated from the ground control station up to 1000 m.
After the landing the drone is transported by the recovery vehicle to the maintenance vehicle. Here the drone is prepared for the next flight and refueled.

Fig.1-4: BREVEL on Winter Trials in Finland

On invitation of the Finnish Forces a complete BREVEL system was shipped to the Kemijärvi-Airfield in Finland in April 1998, north of the polar circle. BREVEL demonstrated successful flights even under extreme wintry conditions at temperatures of - 28 ° C.
Our figure shows the drone after its successful flight and parachute landing just before picking up by the recovery vehicle.

1.3 MÜCKE: Jamming of UHF/VHF Ground Radio Links

The jamming drone MÜCKE is to be developed on the basis of the reconnaissance drone BREVEL.
For example the MÜCKE ground control station is taken from BREVEL as well as the tailless air vehicle configuration.

Instead of the IR payload a broadband jammer of high power in the UHF/VHF band will be installed as payload into the MÜCKE drone. The BREVEL video data link will be replaced by a HF data link. The basic functions of the drone (air frame, engine, flight control, navigation) are fulfilled by unchanged BREVEL components.
The MÜCKE system gets tied to the "ELoGM-Einsatztrupp". In the context of the ongoing definition phase

prototypes with jammer payloads will be ready for the maiden flight in June of this year

Fig. 1-5: MÜCKE on Electronic Combat

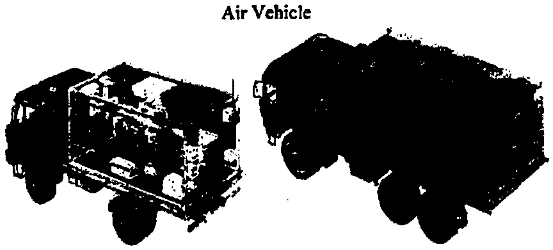
1.4 TAIFUN: Combat against High-value Ground Targets

Within the command responsability of a corps the combat drone TAIFUN attacks ground targets like

- armoured vehicles
- command posts
- logistical facilities
- artillery in firing position
- helicopters on ground

and other high-value targets and will also be committed to block areas.

Air Vehicle



Ground Control Station Launch Vehicle

Fig. 1-6: Combat Drone System TAIFUN

All three drone systems come into being under the common philosophy of "One German Army Drone Family", which was jointly developed with the military user. This philosophy enables the sectional application of technologies, procedures and components for further drone systems as variants for future tasks. This family concept pays off in the service phase by common sequences of operations and common logistics.

2. Technology Basis of Future Drone Systems

2.1 Core Components and Functions

How system variants can be derived from the drone family concept was already shown at the example of the jamming drone MÜCKE.

The existing and arising components which are in accordance with the drone family concept of the German army form a system core, which will be common for all future drone systems. This system core is also available for arms overlapping activities as e.g. for the navy drone or for "Future Lessmanned Aircraft Operations" (FLAO).

This system core comprises the functions:

- mission planning
- mission control and guidance
- flight guidance/control and navigation
- sensor data processing and communication

Besides the advantages for new developments the use of the system core is aimed particularly on the increase of the system reliability, the more economical spare part stockpilling as well as simplification of handling processes and higher interoperability in the ground control station.

The extent and the performance of this system core increases with the development progress.

When developing new drone systems this core will be improved by task specific components like e. g. :

- payload specific guidance, control and evaluation software
- Interfaces

or also by available core components.

On ground the improvement of the system core shall lead to a ground control station usable for many drone systems. The following figures show some examples for the develpoment status of the system core and jointly applicable compoments and represent the starting position for system variants and integral solutions.

2.2 System Core as Starting Position for System Variants and Integral Solutions

A starting position for system variants and integrated solutions represent the following system cores:

Ground Control Station

The following functions must primarily being covered by the ground control station

- Communication

- Mission planning and system control
- Image representation and evaluation

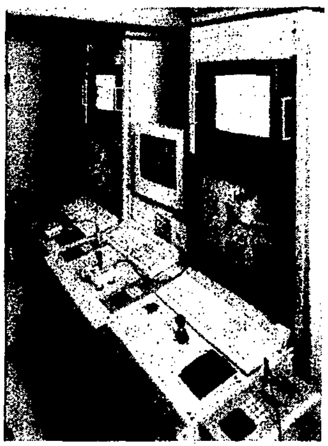


Fig.2-1: Ground Control Station

The goal of the ongoing development is the standardization by using commercial PCs, network technologies and ergonomically as functionally mostly equal opera-tor consoles.

The communications are carried out via terrestrial connections with radiotelephone systems and data links in which SatCom also is used.

Mission planning and system monitoring starts with the planning of the mission on the digital map, in which is prepresented the operational state received via ADLER data link. Direct changes of the running mission during drone flights are possible at any time.
The image prepresentation and evaluation comprises an image/map comparison for navigational purposes as well as a corresponding processing of sensor data and images for target reconnaissance and target localization.

Flight control and guidance system
In context of the TAIFUN development a performance standard is reached for the flight control and guidance system, by which the common usability of additional interfaces is extended as e.g. for friend-or-foe identification and a larger computer capacity is assigned for free programmable mission intelligence.

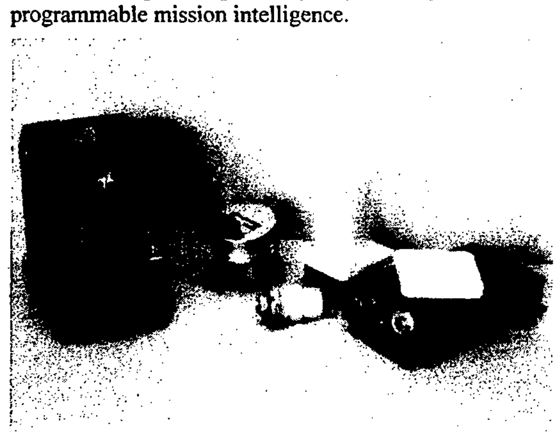


Fig.2-2: Flight Control and Guidance System

Data Links
Still considerable need for standardization exists for the data link connections between ground control station and the flying drone.

The different requirements regarding range, jam resistance, data rates and costs haven't been able to result to a common component till now.

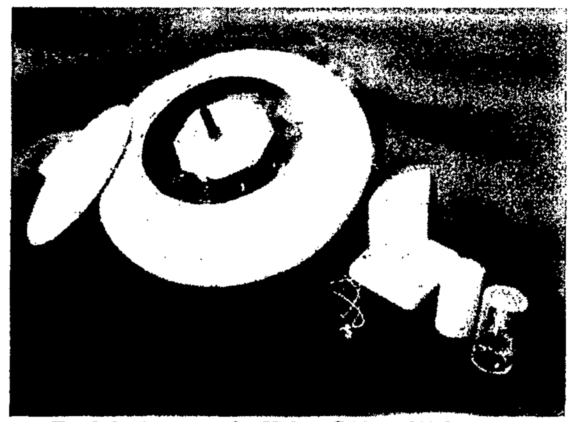


Fig.2-3: Antennas for Video, GPS and Telemetry

Fig.2-4: SatCom Device for Land Vehicles

The current need for far-reaching data links of high data rates for video transmission in real time can be met however in future by the use of SAT COM devices.The starting position for the realization of this solution is available at STN ATLAS taking into account the experience and application of such products which collected STN ATLAS in other divisions of the company.

Engines
A gap of equipment still exists at the engines for drones. Longer flight times and higher speeds require a light kerosene motor in the 32 KW class of low consumption.

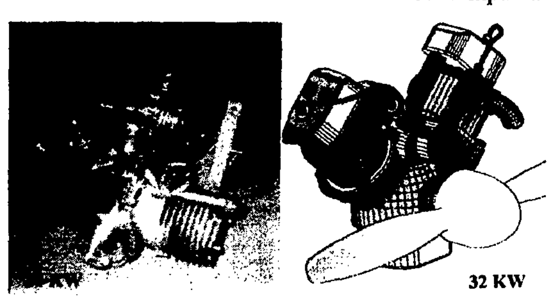


Fig.2-5: Two-Stroke Engines

Stealth Measures

To increase the survivability of drones in the operational area, measures to reduce the signatures in all spectral ranges are absolutely required . This also includes the camouflage against radar acquisition. At the BREVEL radar signature reduction one has to distinguish between radar absorbing material, radar transparent material and radar reflecting material.

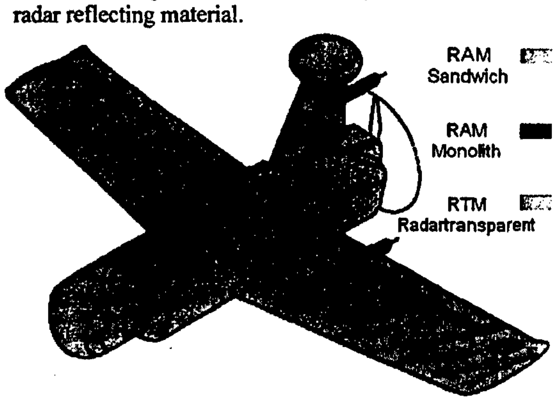


Fig.2-6: Radar Camouflage Design of BREVEL

STN ATLAS disposes of a radar signature measuring chamber especially developed and equipped to measure very precisely small radar cross sections about a broad frequency domaine for real drones and drone components. The measuring results are analysed two-dimensionally to reveal the causing scatter centers.

2.3 Main Emphases of Future Developments

After we have got an overview over the status of the drone family of the German Army now, I like to answer two questions:

a) Which possibilities opens this technology basis?
b) What are the focal points of the development?

To a)

The development of new systems concentrates in future on the integration of available components taking into account new technologies and the supplementation around task specific parts. The use of the system cores and available components facilitate shorter development schedules and prototyping.

To b)

In the area of air vehicle technology longer flight endurance and larger payload capacities must be reached. With this the possibility of applying payload combinations is created. Payload modules with standardized interface shall facilitate to equip the same drone for different tasks by payload exchange on ground.

A higher degree of automatization of the sensor systems must be reached by improved pattern recognition, target classification and sensor data fusion so that the operating team can more concentrate on the original military tasks. Future drone systems must also be tied up to IFF systems.

For larger penetration depths at simultaneous online transmission of sensor data the development progress of the satellite communication must be used. The progress on the civilian sector assures the required data rates. The neccesarily small built in volumes of the SatCom antennas will be reached by the improvement of phased array antennas.

The increasing meaning of operations of the allied forces together with partners of the NATO states requieres increasing demands on communications. The realization of this interoperability cannot be carried out in the context of the running drone programs.

The ground stations must however have the corresponding interfaces to be able to exchange data with the different communication devices so how this happens at the German drone family via ADLER.

With the growing number of drone operations the question concerning their imbedding in the air surveillance / air traffic control has arised onto a decisive meaning. Therefore the drones have to be equipped correspondingly, e.g. with anti collision lights, access redundancy and transponders.

The procedures for imbedding into the air surveillance, e.g. via communication with the drone ground control station, but also for airworthyness and air certification of the drones have to be defined.

3. Future Concepts

For the future concepts of new drone systems the following technological areas are decisive:

- Air Vehicle Technologies
  - longer flight endurance
  - capacity for payload combinations
  - exchangeable payload modules
- Sensor Technologies
  - pattern recognition and target classification
  - sensor data fusion
  - IFF system
- Communication
  - LOS independant, long range data link
  - interoperable communication devices
- Flight control and flight surveillance
  - integration into the air surveillance / air traffic control

3.1 Examples for System Variants and New Systems

In the last section I like to show you some examples, how future tasks can be realized by system variants on the base of the drone family of the German Army or on the base of the system core. The appertaining task areas already are treated mostly in ongoing studies.

A large portion of the tasks can be fulfilled by system variants on the base of the drone family.

Thereto belong:

- RECCE / STRIKE
- Helicopter suppression

- Weather data acquisition
- Reconnaissance of mine barrages
- Electronic reconnaissance
- ABC reconnaissance

for which payloads corresponding to the tasks have to be integrated into the systems BREVEL or TAIFUN

RECCE / STRIKE

The next picture shows the screen splitting of the ground control station simulator of the demonstration program RECCE/STRIKE concept.

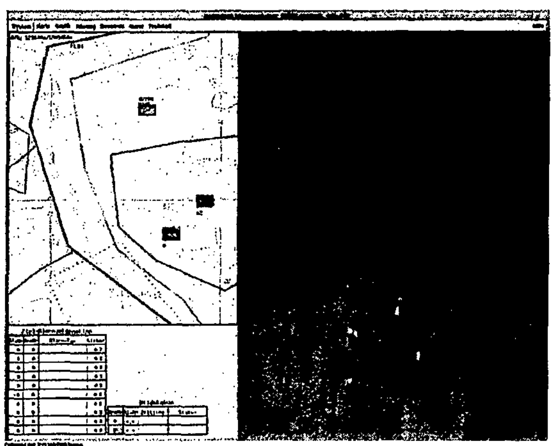


Fig.2-8: Sreen of the Image Interpreter

The prepresentation of flight path of the drone and the acquired ground targets on a digital map are completed by the prepresentation of radar and TV or IR images in correct positions.

The guidance of the drone can be both programmed freely before the start and entered during the flight directly.

Extensive simulations of drone flights with military operators permit as well the operational and system engineering like assessment of the system concept as its purposeful further development.

Weather Drone

The following picture shows an example for a system variant on the base of BREVEL.

To increase the target hit accuracy and to save ammunition for the far-reaching artillery weather data have to be collected from different altitude layers of the target area. For this purpose probes are dropped from the drone over the target area. These probes transmit the weather data to the drone which in turn passes these to the ground control station.

The realization is carried out with modified BREVEL prototypes because it is an integration task. After these here shown drive and wind tunnel trials in the meantime flights with ejections of probes have been carried out successful.

Fig.2-9: Drive Trials for Drop Probe Ejection

Inboard Profile

An additional payload in the range of the center of gravity allows the use of modular sensor components and warheads as well as aditional kerosine tanks to enlarge the fuel stock for prolongation of the flight endurance.

The use of a power tuned engine yields in connection with the integration of a constant speed propeller to an increase of the flight speed.

The external shape of the lightly sweeped tailless configuration of the air frame allows that the compo-nents up to now arranged cylindrically in the middle section of the air frame can be distributed over the two-dimensional structure from now on. Signature specific aspects are influenced positively by this configuration furthermore.

System Elements of LUNA

Not only in the tendency of larger, heavier, longer ranges are future drone developments conceivable but also in the opposite direction of light-weight close reconnaissance systems (LUNA). Trials have been started in this direction also by our company. The main features are:

The air vehicle with

- plug-type wings for low transport dimensions
- GPS for autonomical navigation

Ground control station with

- cross country, self-supporting vehicle as ground control station including
  - two video work stations
  - TM/TC and video data link
  - antenna stack

- catapult lauching gear as test model
  - based on pressure gas for short set-up time

The company EMT develops such a system very successful. The system is presented by one of the following reports.

Far-reaching drone

The tasks of a far-reaching, deep penetrating drone with long dwell time over the target area require drones on the base of the system core.
It becomes in one the platform for further missions with long flight endurance.

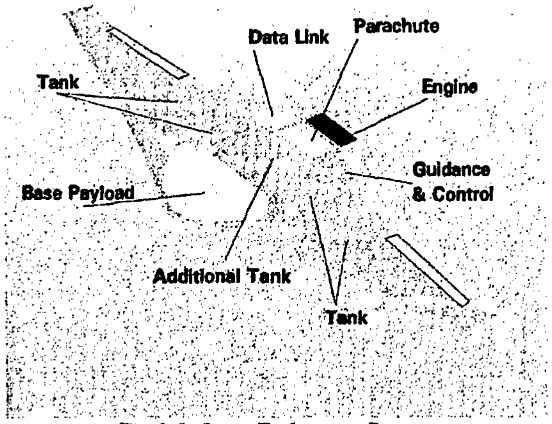


Fig.3-1: Long Endurance Drone

The figure shows a conceptual design for a far-reaching drone with long flight endurance. As design criteria were predefined:

- The use of the system core supplemented by a SatCom device
- Integration of an existing IR payload
- Possibility of an additional payload
- Flight speed up to 400 Km/h for short cruise times
- Mission endurance up to 12 h

Proven techniques for launch and recovery can be applicated on one hand like:

- Booster launch and
- Parachute and air bag recovery

and on the other hand new launching procedures on the base of catapult and conventional methods.

The time schedule "Technical Progress of Drone Developments" shows the termination of the development of the drone systems BREVEL, MÜCKE and TAIFUN representing the starting position of the future drone family of the German Army.

Based on that the system core has reached its highest extention stage in 2002. From this time on a new drone system, e.g. the far-reaching drone can be ready for a maiden flight within 2 years as prototype.

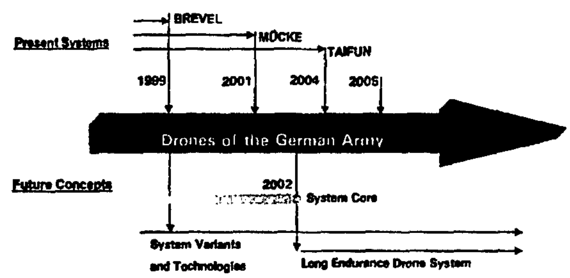


Fig.3-2: Technical Progress of Drone Developments

4. Summary

With putting into service of BREVEL, TAIFUN and MÜCKE the German Army becomes a leading force in the application of modern drone systems.

The drone family can get extended by system variants to cover more recently tasks.

A common usable system core is created by the drone family.

New drone concepts are build up on this system core.

Development activities can be concentrated on task specific components.

Development periods and costs are reduced by integral solutions and prototyping.

Miniature Remote Eye/Ear Land Vehicle

(April 1999)

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Abstract

A miniature remote surveillance land vehicle was developed for experimental real-time video/audio data acquisition in air defence live-fire training. A mobile sensing platform was needed to acquire the video/audio data at a close proximity to the gunners, without breaching safety requirements. The platform was designed to be small, conforming to the need to transport it as a passenger luggage on a commercial airline. A commercially available ready-made largest 1/10 scale Radio Control (R/C) hobby vehicle with 4 wheel drive system was chosen as the platform. It incorporated pre-built drive, suspension and steering systems. The chassis was fitted with 4 kg payload for a total weight of 8 kg. It was very stable after adding damping shocks and extending the chassis. It was capable of climbing 15 cm sidewalk curbs, driving down off 20 cm ledges, climbing 10 to 20° slopes and through about 10 cm of light to medium snow with its original rubber tires. Its total travel range was shown to be over 800 m. The control function for the vehicle and its sensing system was achieved using an R/C unit whereby a channel-select plus channel signal multiplexing system was developed to operate one selected channel of 7 possible at a time using only two radio channels. The sensing capability of the vehicle involved a digital video/audio recorder positioned at the front of the platform and a miniature camera and microphone assembly placed on the top of a telescoping mast with an ultralight pan-tilt unit based on a micro R/C servos. The video and audio signals from the mast-mounted package were transmitted to the control station using a repackaged commercial transmitter. Testing and use of the vehicle determined operational limits of its performance and led to its modifications and enhancements.

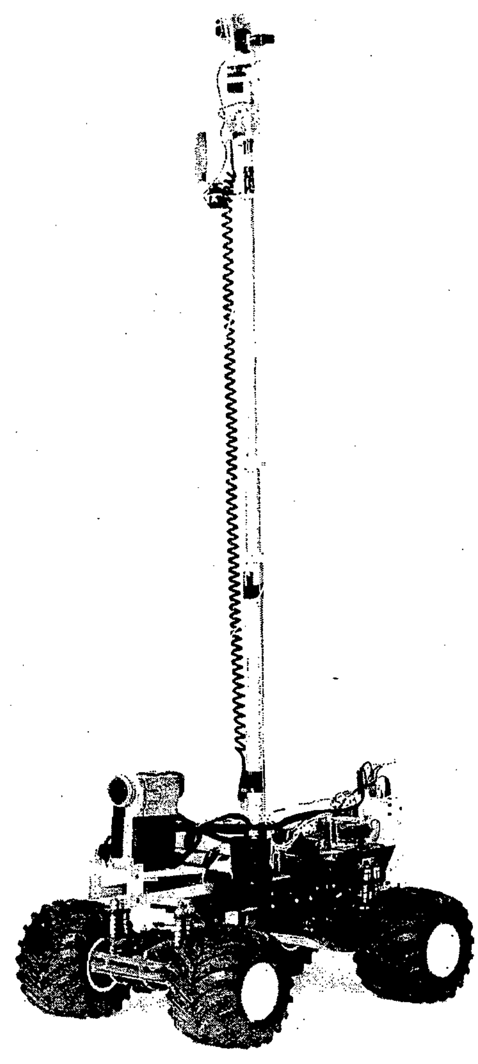

Figure 1. The miniature surveillance vehicle with fully extended mast.

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

Introduction

Data acquisition work has been carried out during air-defence field firing trials of the Canadian Forces over a number of years for a variety of reasons. The practical experience from this work and interaction with the operators brought up the need to document performance of the gunners as well as the missile launchers during the exercises. However, tactical scenario of the exercises and safety considerations, combined with the variability in the activities and the scene, made it practically impossible to acquire useful video and audio data reliably from remote, fixed video/audio systems. This led to the desire to have a remotely controlled camera/audio system that could be positioned at will without requiring any hands-on adjustments and which would not be subject to the range-safety restrictions imposed on personnel. It was also desired that this system have a real time video link to the control area so that remote camera alignments and fields of view could be seen and adjusted as required, as events evolved. It was particularly important to adjust the location of the camera so as to avoid blocked-view situations which occurred with a fixed-view camera. This could be naturally accomplished with a mobile platform. A mobile platform would allow for placement of a camera even in the down-range area which is not accessible to personnel on account of the safety issues.

The ideal objective was also to have the system small enough to go as a normal luggage on a commercial airline. This objective imposed significant weight and size limitations. It also precluded gasoline as the source of power since the fuel vapours create a hazard in transportation. Moreover, noise and controllability issues of gasoline engines create unnecessary problems when compared with the inherent quietness and ease of controllability of electric drive. Battery power, therefore, became the main alternative.

Upon deciding to develop a miniature remote eye/ear land vehicle that would conform to these objectives, a time and effort conservation approach was taken in conceiving its design. It was also desired to keep the costs down. With this in mind it was noted that the vehicle could consist of a set of subsystems all 'glued' together. The aim was to minimize the effort. This lead to a market survey of hobby R/C vehicles already equipped for remote radio control operation as a source of a pre-built chassis with power, suspension and steering.

Initial Considerations

Method of Project Development: The aim of the project was to design the smallest, lightest and yet economically practical and operationally functional remotely controlled vehicle with camera and microphone functions. The approach in the design of the vehicle was driven by the need to maximize its range of travel. It is well known that heavier vehicles have greater power consumption and with a fixed power source, their range decreases correspondingly. The weight of a battery-powered vehicle consists of vehicle chassis, including its payload and batteries. The low energy consumption aim was therefore turned into the goal of minimizing the weight of the vehicle. An iterative process was applied to optimize the match between the payload requirements and the chassis/payload capability. The market was searched for subsystems to maximize the system capabilities, minimize its cost, minimize its weight and satisfy the compatibility requirements. The following sections address issues related to the planning of the capabilities and design approach for the vehicle. Functional aspects, chassis and payload capabilities were considered. The payload had to be determined first before the chassis could be addressed. The payload was to include: video/audio sensing, video transmitter, the channel mutiplexer/optoisolator, battery and battery switching circuit for the main drive motors, telescoping mast for bird's eye view camera, radio receiver with antenna, and radio battery and electronic speed controller for the wheel drive motors.

Video System: A video unit, either a camcorder or a discrete camera with a separate VCR was the central item in the payload of the vehicle. The video capabilities were to include a camera head with lenses, preferably mounted on a pan-tilt and/or leveling mechanism and transmission or recording equipment to allow monitoring and logging of the video scene. It was anticipated that either option would represent a substantial load. Hence, the camera was to be mounted centrally on the chassis. In operation, low quality video could be used for navigation purposes and then the system could be switched over to high quality for actual data acquisition and recording. Data acquisition had options of recording at a base station after transmission and recording on the vehicle. The on-board recording option was limited by tape length while base station recording could be affected by transmission quality. Video transmission was also required for camera alignment and sighting.

Once the very light and very small tape digital camcorders became available, all heavier and larger analog units were eliminated from considerations. Sony, digital DCR-PC7 with 60 min quality recording tapes (or 90 min in the extended play mode) was chosen as the camcorder for the vehicle. It weighed 621 g with a new Lithium Ion battery with 90 min. capacity. It used proprietary image compression technique before laying it to tape. The overall quality of the compressed image was slightly lower than Hi-8. However, this was a reasonable trade off for the smaller weight and size.

The digital camcorders functioned as auto-focus, auto-exposure camera system without any external control, unlike discrete camera systems (e.g. Sony XC- 777). With the use of an additional control signal, the camcorder approach offered a fully motorized zoom lens function, again at a large weight, volume and cost advantage over discrete camera with a motorized lens, although with a lesser zooming power. The digital camcorders had NTSC composite video output which could be transmitted and monitored back at the base station.

A mast-mounted camera was also added. It would be particularly useful for navigation. The plan was to have a short mast for general travel. It could telescope on command to greater height. The telescoping capability would serve two useful purposes. It could allow to "see" overtop of obstacles, such as toll grass or bushes. It could also help video transmission quality by raising the mast-mounted transmission antenna to facilitate better signal propagation. The camera was meant to be very small and lightweight and was also to be mounted on a similarly extremely small and lightweight pan-tilt mechanism that would be at the top of the mast. MicroVideo PC37XSA B&W camera was chosen. It came with a relatively wide-angle lens at 78° field of view and an onboard microphone, both weighing only 31 g.

Video Transmission: The video transmission can be accomplished in many different ways and means, each with its technical and regulatory pros and cons. An unlicenced alternative, explicitly noted as being FCC Part 15 approved, was chosen for the project. Two frequency bands, 900 MHz and 2.4 GHz, are generally used in FCC Part 15 equipment for video transmission. Each system typically consists of a transmitter and a matched receiver. Wavecom 2.4 GHz units offered by Microvideo were chosen as they operate in the less crowded band. The units could be operated in one of 4 channels within the 2.4 GHz band. Therefore, one could operate 4 different send-receive pairs in the same area. The basic turn-key NTSC color video plus stereo audio transmit-receive pair was also advantageous. A higher gain receiver was also acquired to facilitate a longer range transmission. Enclosure of the sending unit was substituted with a lighter, smaller one. Only one audio channel was connected as the camera had mono sound. A 10-cell 12V battery pack used sub-C Sanyo NiCd cells. The cells were arranged in a compact enclosure which was mounted crosswise on top of the chassis, near its center.

Chassis: A basic task was to source a chassis that would be as small and light as possible while being able to carry a nominal payload. It was to have the ability to drive reliably over and through different environments without getting stuck. It was also to have a stable, low center of gravity so that the chassis could be oriented in different directions on a slope without danger of tipping over. A contradictory desire was to have lots of ground clearance under the chassis so that relatively large obstacles such as rocks and stumps could be driven over without getting hung up. It was also desirable that the chassis should have a suspension system such that a smooth ride was delivered to the camera and VCR payload. A contradictory objective was that the suspension should not be soft and compliant because the chassis would then be subject to movement induced by any gusts of wind. Deployable stabilizers could be added but their weight and complexity would be detrimental. With considerations for the chassis features, the video and radio equipment, a general size for the payload was anticipated to be less than 4.5 kg.

Use of tracks was considered to achieve very good all-terrain mobility. However, detrimental derailing tendency of tracks with increased traction and lack of tracked options, compatible with the anticipated size of the vehicle, led to the consideration of wheeled alternatives. Wheeled chassis were developed by the R/C hobby industry. They addressed the issues of miniaturisation, adequate strength, durability and low cost. One of the overall benefits of using a ready made large scale R/C chassis was that it had drive, suspension and steering systems all pre-built and ready for use. The practical issue was to find a model with suitable overall size and strength. The common R/C size is 1/10 scale (about 30.5 cm long vehicle chassis) with electric 4-wheel drive. This was too small to fit the basic VCR and the other equipment. The largest chassis were gasoline-powered 1/6, 1/5 or 1/4 scale with about 61 cm long wheel-bases and rear axle 2-wheel drive with a full differential. For this application, the gasoline engine would have to be replaced with an electric motor. Lack of compatible assemblies precluded use of more robust replacement differentials and creation of a 4-wheel drive which would be more suitable for off-road driving with a larger payload. The Clod-Buster "Monster Truck", the largest 1/10 scale commercially available 4-wheel drive chassis was discovered. It had all-wheel steering, 15 cm diameter heavily treaded tires, a 27 cm wheel base and an overall width of 37 cm across the outsides of the tires. The vehicle weighed about 3.6 kg without the cosmetic truck body. Each wheel plus tire weighed 380 g which meant that the four wheels plus tires weighed 1.5 kg total. The drive was done with two separate motors plus differential axles. It offered an excellent initial suitability for off-road use.

Development of Clod-Buster Based Vehicle

Drive Train Tests: Various bench tests were carried out with the Clod-Buster 7.2 volt 540 motor differential assemblies with plastic gears. Data were taken about energy usage and motor current draw that is directly related to generated forces and torques. Since both ends of the chassis had an identical motor and differential assembly, only one was tested. Two different modes were used: one where both wheels spun simultaneously, involving one set of gear meshing and another where only one wheel spun and the differential action was invoked. 2.6 A current was needed to break the static friction and start the gear train with no external loading. Only 1 A was required to maintain spinning. The spinning freewheel rpm increased as a function of the applied motor terminal voltage: rpm = -11.28 + 73.88 x V. The actual speed would be lower on account of the load from rolling resistance and losses in the electronic speed control for the motor.

The single motor/differential combo was then tested under load. The current requirements would correspond to initiating forward motion of the vehicle against rolling resistance or a slope: Motor current (A) = 1.63 + 0.19 x Torque (N-m). If the vehicle weighed 4.5 kg and rolling resistance was neglected. with the 15 cm diameter wheels, an incline of 10° would require a forward thrust of 7.7 N which should require current draw of 11.3 A. The motor's terminal resistance was measured to be about 0.17 ohms. The motor near-stall at 7.2 V supply would draw very high current, mitigated by the systems resistance and onset of motion. At slow armature rotation, the motor currents near 6 A were taking only 1 V on the motor. The rough analysis shows that the chassis would have a fair amount of thrust capability, despite the seemingly small battery voltage of 7.2 V.

Another test with one wheel locked indicated that differential did not incur significant losses when their action was invoked. The back driving of the differential was also tested in analogy to the vehicle starting motion down a slope. At 0.34 N*m torque. the motor/differential would back drive without any power applied. That would imply that in the 10° slope example, its 7.7 N thrust would be held by the pair of differentials, meaning that the vehicle would not roll down when parked down hill with the power off.

It is estimated that the drive train is about 90% efficient as it uses spur gears and it is likely a non-issue when compared to the real world rolling resistance as a function of terrain and vehicle weight.

Telescoping Camera Mast: A telescoping camera mast was needed for the vehicle to facilitate the diverging needs associated with the (low center of gravity) mobility on one hand and the highest possible camera position in a static state on the other.

There was a need for a telescoping mast that would be very light, operated with low power, achieve chest-height on deployment and that would stay at the height it was moved to after power was removed from its motor. It was to have a minimum height when retracted. Mast designs with 2, 3 and 4 stages were pursued. In the final version, a 450 g, 3-stage mast was developed, placing the camera at the level of 140 cm above ground. Figure 1 and Figure 2 show the extreme positions of the mast on the vehicle. The motor for the mast was a servo, modified to be a gearhead motor with unlimited turning of its output shaft. The drive used a pulley and a slip clutch. Custom made teflon slip bushings were used for the telescoping assembly. A positive drive string system was used to lift the stages with a string in a closed loop passed over pulleys at the top edges of each mast piece and then down under pulleys at the bottom edge of the next inner mast piece. The string had to pass through the gap between each pair of sliding members. The system worked on the principle that the string could lift from the top edge of the outer member upon the bottom edge of the next inner member. When a member rose to its most upper position as defined by hitting a travel stop, the string would simply roll through the ball bearing pulleys. The friction of the string over the pulleys was almost zero and it was this that allowed the use of a stock servo as bottom drum pulley motor.

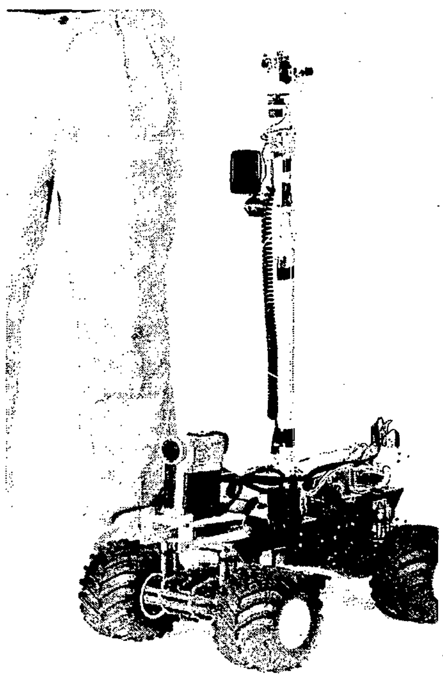

Figure 2. The vehicle with its mast collapsed.

Initially, a separate fixed-length mast was made for the video transmitter. It was substituted with a special mount made to hold the antenna near the top of the telescopic mast, at a sufficient radial offset so that the mast would not be in the transmission path. The antenna transmitted in an approximately 180° arc pattern from its face but the strongest transmission was on its axis. The range of the antenna positions on the mast was decided based on two factors. One was to have the main range of motion pointing away from the mast. A second was to consider what situations it would operate in so that transmission could go unimpeded. Typically, it would be pointed rearwards or sideways from the vehicle.

Mast Camera Pan-Tilt: A very light, low precision pan-tilt unit was made for the mast-top camera. Microsize R/C position servo was used as the entire drive, electronics and axis mechanism for each axis of motion. This was possible because the extremely light weight camera was not likely to overload the plastic gears, shafts and bushings of the servos. The Supercircuits PC37XSA black and white camera with microphone/preamplifier and the pan-tilt assembly weighed about 140 g. It is shown in Figure 3. The clear plastic box around the camera was only 3.8 cm square on its front.

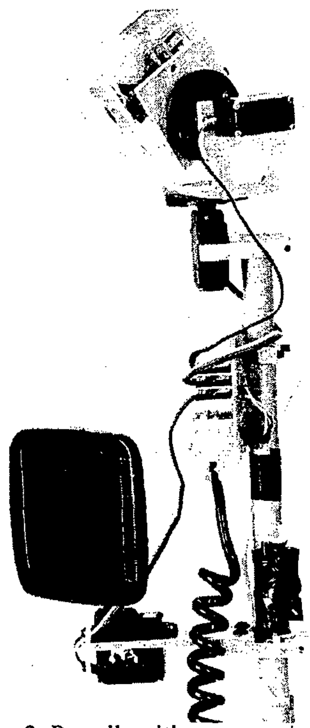

Figure 3. Pan-tilt with a camera/microphone assembly and video transmitter antenna at top of the mast.

Multi-Channel R/C Radio Operation: There was a need to use a number of R/C radio channels to control various functions on the vehicle, such as the pan, tilt, antenna orientation and steering. Two 8 channel radios were acquired with the expectation that they operate on different frequencies. However, their specialised channel mixing functions were not advantageous to this application. A channel select plus channel-signal multiplexing system was developed which used 3 output channels that were relatively directly coupled to outputs in the radios. A multipole wiper switch was modified and coupled with a servo, providing the means to switch signal and power connections. The signals were multiplexed using one signal as a chooser channel and another channel as the command to be sent. Thus, the radio's two joysticks could be used in a predictable and relatively simple way to operate seven channels. The third channel was connected directly to the electronic speed controller for the drive motors on the wheels. An opto-isolator was used to provide a barrier between the long servo lead wires that went up the masts and to various locations on the chassis and the radio receiver. The isolator also allowed separation of the receiver power from the device loads to extend its run time. The left-right action of the right joystick was used for an intuitive steering control. The front-back action of the left joystick was connected as the control for the channel selection because it did not have a spring return action. The selector serviced steering, mast height, mast camera pan, mast camera tilt and video camera orientation. It also had the capability to serve tilt for the camcorder and select video output to the transmitter.

Initial Testing and System Modifications

In the initial tests, extreme *fore-aft rocking* of the chassis during acceleration, deceleration or when on bumps indicated that the chassis was too tall or too top-heavy for its length. Moreover, the masts and video battery pack occupied nearly all of the central chassis region and there was no space for a camera which was yet to be mounted. The chassis wheelbase was therefore extended nearly 50% to 39 cm. The completed vehicle weighed about 7.3 kg, effectively doubling its original weight. The extended chassis was very stable. It was capable of climbing up 15 cm sidewalk curbs and driving down off of 20 cm or 23 cm ledges. It was capable of climbing 10° to 20° slopes. Some amount of maintaining momentum in driving style helped significantly in overcoming small surface irregularities on the slopes.

Side-to-side rocking motions induced from even the smallest bumps in the grass were corrected with the use of replacement coil-over shocks which could be filled with oil of desirable viscosity and thus provided more effective damping. The shocks also allowed preloading adjustment thereby to take care of inequality in load balancing.

Differential action was found to halt progress if one wheel of a differential set lost traction and started spinning. An electronic differential action occurred when the two motors were wired in series in economy mode in that, if one motor broke free, the total current dropped and with it the drive force dropped. In parallel wiring power mode each mechanically differentialled wheel pair could develop its own thrust regardless of the slippage of the other wheel set. A traction problem occurred when the stiffly suspended chassis became supported on a pair of diagonally opposite wheels in that both drive wheel pairs would lose drive as the suspended wheels spun freely with little or no contact force with the ground. Softening of the preload in the shocks to increase the suspension compliance allowed larger obstacles to be accommodated on the diagonal wheels before loss of contact pressure on the other two diagonal wheels occurred. However, softening of the suspension increased side swaying. A smooth nylon sheet skid plate was attached to protect undercarriage from gouging during contact with protruding obstacles.

The steering was not strong or rigid enough despite the increased servo strength to 0.812 N*m, resulting in uncontrolled course changes when an obstacle would hit only one wheel, jarring the steering. This occurred because of the anti-breakage spring-torque link in the steering linkage. Excessive tightening of this link was discouraged by the increased risk of breakage in the steering system.

The pan-tilt with the top segment of the *mast* was panning in random motion whenever chassis hit a bump. The pan-tilt off-axis center-of-mass created the problem. An anti-rotation feature was implemented on the mast to prevent the problem. It was a piece of piano wire glued to the side of the tube to form a straight, uniform sized ridge.

The *range of travel* of the vehicle was shortened significantly when carrying its extra payload and rolling in the grass. The stock battery was replaced with three 1500 mAhr packs to extend the range. A three battery switching circuit was set up to protect the NiCd batteries from discharge below 1.1V.

Performance Tests of the Vehicle

Preliminary testing of the vehicle mobility and communications was carried out during a summer air-defence firing camp and later, during a snow storm.

The vehicle was driven for an *endurance* test from a control position at a range, over a raised road about 150 m away and out to the firing point, another 70 m further. Direct external viewing was used in the control process. The ground was relatively hard, flat, sometimes grass-covered terrain with bumps and protrusions significant for a miniature vehicle. The first run was via direct view from the control position. At the road, the vehicle became hard to control because it was hardly visible at the distance. Some traction problems occurred there when the vehicle encountered a gravel ridge. The vehicle was initially run in the slower economy mode to lower the chances for a driving accident. Once the motor was switched to parallel wired power mode, the vehicle climbed up the incline and over the road ridge. Controlled by an operator at the road, the vehicle proceeded to the firing point, maneuvered around the firing point, climbing up the mound a few times. Then, it was driven back to the road, crossed the road and was driven all the way back to the base for a total of 400+ m travel. This completed the basic endurance test. The opportunity to drive it till it ran out of battery power was then exercised. At this point in time the range observation tower was used and found to offer a good view all the way from the base out to the firing point. The vehicle was driven back out to the road at which point it seemed to stall. A thermal shutoff had occurred but once it cooled off the vehicle was driven out to the firing point again and driven all the way back to the base for a new total of 800+ m travel. Battery power was still available at that time but the test was terminated.

The vehicle was also tested for *terrain traversal* capability. A small hill was used for the test. In addition to the incline there were irregularities on the surface which tended to form small segments of higher incline. The mast was the only way the vehicle could be seen in tall grass when climbing the mound. Inconsequential tipping was seen when the vehicle was driven with one side's wheels over a stone. More significantly, on account of the insufficient steering strength, the stone turned the wheels, altering the direction of the ascent. Then, the vehicle would hit the bump or depression, possibly at speed. There was no way of predicting the hazards before driving into them, particularly in the tall grass or when operating at a distance. There was a potential hazard of flipping the vehicle when encountering substantial obstacles such as stones, falling into small holes or depressions created e.g. by truck wheels in mud. However, the vehicle was stable even when encountering unplanned obstacles at speed, showing quite a resistance to flipping over. The chassis proved quite robust despite its overloading as compared to its intended commercial purpose. Considering the size of the vehicle, its terrain traversal capability was judged to be excellent. Perhaps the best example of its successful performance was a crossing of a plot where brush and small trees were cut at about 8 cm above the ground. The tires and suspension absorbed the 8 cm tree stumps without excessive perturbation.

The colour digital *camcorder* mounted at the front of the vehicle was tested in a navigation task. A styrofoam wedge was used to trim it to an angle that balanced some land vs. sky such that waypoint navigation was possible. The camera was not equipped with its pan-tilt unit. Rough panning was accomplished with vehicle turning but tilting was not easily achievable. Navigation was difficult with the approximately 30 cm height of the camera lens above the ground. The viewing attitude did not allow for good scoping of the ground layout for any significant distance ahead. Trying to see through the tall grass was distracting. Moreover, the autofocus on the blades of grass, made the desired background blurry. Outdoor lighting conditions posed a difficult task for the good automatic iris capabilities of the camera. The brightness of sky and darkness of land could not be seen simultaneously, particularly on an overcast day; the sky was too bright and/or the land was too dark. A moderately wide field of view was required for onboard camera navigation so that waypoints could be retained in view despite vehicle motions. A narrow field of view was required to see any useful detail at the activity site of interest if a moderate and unobtrusive stand off distance was to be maintained. Color provided much better depth and feature perception than the black and white mast-top camera. There was some degree of picture rocking and shaking due to chassis motions, the amount of which varied with how rough the terrain was.

The *mast camera* imagery was also used for remote navigation of the vehicle. The very local, semi-bird's eye view from the mast camera was particularly useful for way-point navigation, for perceiving ground features and general ground layout ahead of the vehicle and for driving over and around obstacles. One could nearly intuitively pan and tilt it as if it was one's own head and eyes to attain situational awareness. The camera could view the vehicle wheels, as shown in Figure 4, and it could also pan-tilt to survey the surroundings to get a bearing. The camera could be tilted front-wards to see more range in front. The bird's eye view mast camera was more useful than a lower camera in seeing obstacles and in getting a better down-angle view from which to better see land features ahead. For navigation, the black and white image provided less object depth. differentiation and perception usefulness than a color image would. Once near the area of interest, the wide field of view of the mast camera was less useful for observation of activities of personnel within the field of view.

The *video transmission* equipment worked very well but required a clear line of sight between the antennas. The video was found to break up when natural land obstacles or tall grass impeded the line of sight. This occurred quite easily with the vehicle mast set to its lowest position. When the base receiver antenna was elevated, the video transmission was successfully tested to 700 meters and was expected to be able to go much further, provided the line-of-sight criterion was satisfied. The directionality of the antenna setting was not critical but obstacles such as tree or brush in the way of the signal degraded it significantly. When operated in a courtyard, the 2.4 GHz video transmission suffered reflections from the building walls resulting in image breakup.

Some power or *current consumption* tests were done with the vehicle fully loaded. Current measurements were done for both power and economy modes of motor operation. few speed ranges and on various surfaces: flat pavement. level mowed grass and 10° slope mowed grass. In the last case, in series-wired motor mode, the motors used 12 to 13 amps and the vehicle could barely climb the hill. The equation from the earlier bench tests was converted to a form with forward thrust. Knowing that 15 cm dia. wheels were used: motor current in amps = 1.63 + 22.0 x wheel pair thrust in N, yielding 10.2 N thrust per axle. This implies that the total of 20.4 N thrust was used to barely climb the hill in the series mode. The calculated thrust for 10° slope is 11.6 N. The difference between 20.4 N and 11.6 N would be the extra rolling resistance caused by deformation of the tires and softness effects of the grass and soil. This is a significant increase over an idealised calculation. It confirms an expectation that ground conditions are very significant in drive train loading.

The vehicle was also tested for *snow and cold weather performance* (traction and driveability). It was capable of ascending gentle slope mounds in 2.5 cm to 5 cm snow. With this snow coverage, it was also mobile on a road with small ridges of snow created by cars. However, it got stuck in hard-packed snow drifts 10 cm to 12.5 cm deep. Backing out with some wheel spinning was successful in some conditions. Rocking motion did not always dislodge it either when stuck via diagonal support which allowed differentials to act, spinning the unsupported wheels freely. To reduce the diagonal supporting action, the preload was reduced on the front wheels shocks. The vehicle was then going more effectively over discrete obstacles such as the tire ridges in the snow. The more compliant suspension was still subject to limitations when substantial obstacles were encountered. Aggressive driving created significant snow spray which eventually affected the drive circuits of the unprotected payload.

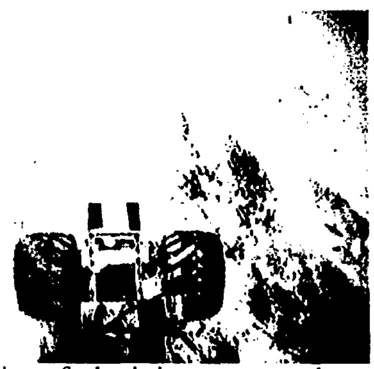

Figure 4. View of wheels in snow, seen through the mast-top camera.

Conclusions

A miniature surveillance vehicle has been successfully developed and demonstrated to satisfy the basic intended objectives. The fully loaded 8 kg vehicle was shown to have a functional capability of traversing a typical range terrain with the power capacity to travel over 800 m. Its image acquisition and transmission capability was satisfactory but some enhancements need to be implemented to make its use easier and more flexible; zoom control on the camcorder and change the mast camera to a colour unit would be particularly advantageous. A video switching selector circuit for alternating between the camcorder and the mast camera, and tilt for the camcorder have been already implemented.

It was observed that travelling around obstacles was the most prudent approach to reliability and energy use conservation.

U.S. Predator Operations – Update

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Bibliography: This information for this paper has been extracted primarily from a paper titled "The Use of Predator in Bosnia – Lessons Learned" produced by Peter Wiedemann of the Joint Strategic UAV Program Management Office in May 1997. The information from that paper has been updated to March 1999.

Summary: The U.S. Predator unmanned aerial vehicle system produced by General Atomics Aeronautical Systems, Inc. has completed three extended operational deployments and has recently commenced a fourth deployment in support of United Nations and American operations in Bosnia-Herzegovina. The Predator system has also recently commenced a deployment to a site in Kuwait. Predator provides operational commanders and their intelligence staffs with valuable and timely live imagery and imagery derived intelligence, often not available from any other source. Through the conduct of these deployments, the operational concept to make best use of the real time reconnaissance capability of Predator has continued to evolve. This paper will provide an overview of the system and a description of the operations with a focus on the changes that have occurred since the original deployment in July 1995.

Background: The experiences of military commanders in operation Desert Storm, who were frequently unable to get timely imagery intelligence on targets of interest, caused them to recognize the requirement for a high capability theater controlled unmanned tactical reconnaissance system. With the advent of the innovative and highly streamlined procurement mechanism call Advanced Concept Technology Demonstration (ACTD) which allows the U.S. government to rapidly field equipment in emerging technologies, the Predator system was born. The Medium Altitude Endurance UAV or Tier II ACTD program was initiated in January 1994 to meet the following requirements:

- Continuous coverage (24 hrs per day, 7 days per week) coverage over a target 500 nautical miles from the operating base.
- Real-time communication with the air vehicle beyond line of sight (LOS) range.
- Capability to detect and identify typical mobile targets from a slant range of at least 15,000 feet, the requirement designed to allow the system to operate out of range of small arms and shoulder fired weapons.
- Minimum service ceiling of 25,000 feet to allow operation over elevated terrain while maintaining 15,000 feet slant range
- Provide a visible light sensor capable of producing motion imagery to allow the controller to acquire and monitor targets for extended periods of time
- Provide an infrared sensor capable of producing motion imagery of targets at night or of targets with significant thermal signatures.
- Synthetic Aperture Radar (SAR) to allow imaging through clouds day and night.
- Operate under the control of the theater commander
- Provide the capability for rapid deployment using C-130 or larger airlift vehicles and to be operational within 6 hours of arrival at the operational site.
- Produce releasable imagery at low classification levels to allow maximum dissemination and usage.

The ACTD procurement, which virtually eliminated the lengthy analysis and review processes which cause standard procurements to take many years, allowed the Predator program to move ahead rapidly and meet the following milestones:

- Contract award — Jan 94
- First flight — Jul 94
- Training start — Oct 94
- JTF-6 Demo — Feb - Mar 95
  - Border Patrol/Counter Narcotics
- Roving Sands — Apr - May 95
- JSOC Demo — Jun 95
  - Special Forces
- NOMAD VIGIL — Jul – Oct 95
  - JTF Provide Promise
  - Operation Deliberate Force
- USCS — Oct – Nov 95
  - Coordinated ops with P-3
  - Border Patrol/Counter Narcotics
- COMTUEX — Nov 95
  - Maritime Operations
- SSN Demo — May – June 96
  - Control from submerged SSN
- Production Program Begins — Sep 96
- NOMAD ENDEAVOR — Mar 96 – Dec 97
  - Joint Endeavor
  - Joint Guard
- NOMAD ENDEAVOR — Mar 98 – Nov 98
  - Joint Guard
  - Eagle Eye
- JOINT FORGE — Mar 99 – pres
- SW ASIA — Jan 99 – pres.

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

System Configuration: The original concept of operations for the Predator system called for only "light" exploitation of imagery at the GCS with the resulting still imagery to be directly disseminated to an intelligence (INTEL) facility at the Joint Task Force (JTF) Headquarters. The INTEL facility would then perform the traditional formal exploitation of the still images and generate formal intelligence reports. This was determined to be impractical and the decision was made to co-locate an exploitation facility with the Predator System. The facility, now used routinely in all deployments, is known as the Rapid Exploitation and Dissemination (RED) cell. It houses intelligence analysts and workstations in a portable van.

System Equipment: The operationally deployed Predator system consists of equipment provided by the contractor and equipment provided the U.S. government. While the system configuration varies depending on the operational site, the following listing identifies the basic equipment used in the support of Bosnian operations.

Contractor supplied equipment consists of:

- Predator aircraft equipped with:
  - EO/IR visual sensor system
  - Synthetic Aperture Radar (SAR)
  - Ku band satellite datalink
- Ground Control Station configured with:
  - dual pilot and payload operator (PPO) control stations
  - Data Exploitation and Mission Planning Consoles (DEMPC)
  - SAR Workstations
  - Ku band satellite datalink module
- Ground Data Terminal (GDT) to support the C-band LOS data link
- Ground Support Equipment for operation and maintenance of the system
- Additionally, the contractor supplies personnel to provide technical support for the maintenance and logistics of the system.

Government supplied equipment consists of:

- Trojan Spirit
  - half used for Ku band control of the Predator
  - half used for the dissemination of intelligence data from the RED Cell
- RED Cell
- Secure satellite communication with the Combined Air Operations Center (CAOC) and the Joint Analysis Center (JAC) used for:
  - transmission of still images and reports
  - tasking

System Operation / Product Dissemination: The Predator system components function as follows:

- GCS
  - performs mission planning on DEMPC
  - controls Predator aircraft through PPO console
    - C-band LOS datalink
    - Ku band satellite datalink
  - controls EO/IR payload through PPO console
    - C-band LOS datalink
    - Ku band satellite datalink
  - controls SAR through SAR Workstation
    - Ku band satellite datalink
  - sends motion video overlaid with selected telemetry to RED Cell
  - grabs and sends SAR frames to RED Cell
- RED Cell
  - receives tasking from command centers via secure satellite network
  - adds narration to motion video from GCS
  - compresses video and audio using MPEG-2
  - disseminates compressed information to command centers and other users via VSAT
  - exploits still frame images from video and SAR and disseminates with reports via secure satellite network
- JAC Molesworth
  - routes compressed information to other users
  - stores images and reports
- Command Centers
  - receive and decompress video and audio for review
  - receive and review still images and reports
  - provides tasking to Predator (and other) operational sites
- Other users
  - receive and review selected product

Mission Tasking: Field commanders initiate the tasking process by providing intelligence requests that are converted into target lists and Essential Elements of Information (EEIs). These are combined, validated, and assigned to the appropriate platforms (i.e. Predator) at the CAOC. The target assignments and airspace allocations are integrated into the Air Tasking Message (ATM) which is routed to the airspace users

Mission Planning: Upon receiving the ATM, the RED Cell analysts perform detailed research on each target by accessing data bases containing earlier imagery of the target areas. This is done to provide the payload operators with the necessary information to facilitate target recognition and acquisition. The geo-coordinates of the targets are also verified. The information is then passed to the mission planners in the GCS who are simultaneously acquiring weather and other pertinent data. The mission planner starts with a digital terrain map of the transit and target areas. Keep out and threat areas are plotted and each target (referred to as a Collection Point) is plotted. Next waypoints are plotted and each waypoint is identified with altitude, airspeed, and several other characteristics including sensor parameters for Collection Points. The mission planners also create an emergency plan to direct the aircraft back to the base in the case of datalink communications failure.

The mission planning software then provides a series of automated checks to verify the viability of the mission plan. The parameters that are checked include fuel usage, climb performance, terrain avoidance, continuity of satellite communications, etc.

Mission Execution: The Predator aircraft, properly configured for the selected mission, is launched at the appropriate time by a pilot "flying" from the cockpit-like PPO console and controlling the aircraft directly through the C-band LOS data link. The aircraft autopilot system enhances handling stability. The pilot uses a TV camera in the nose as the "pilot's eye" for viewing what is in front of the aircraft.

Although the Predator can be programmed to collect intelligence on targets in a fully autonomous, this is not the usual practice. The payload operator typically controls the optical sensors manually through his/her own PPO console. Imagery from the selected optical sensor appears on the monitor in front of the payload operator. The imagery is also sent from the GCS to the VSAT system for dissemination and to the RED Cell for frame grabbing and annotation.

SAR intelligence is always collected in the pre-programmed mode and is supported only by the Ku band satellite data link, not by the C-band LOS data link. The "waterfall" display appears on the SAR workstations in the GCS. 1000 by 1000 (pixel) areas can be frame grabbed and sent to the RED Cell for exploitation and export.

Mission Application: The system has been used effectively in support of the following missions in Bosnia:

- Humanitarian Assistance Monitoring
- Troop Protection
- Target Coordinates
- Search and Rescue
- Pre and Post Strike Surveillance (End-to-end support of the Look-Shoot-Look Model)
- Dayton Accord Compliance Monitoring
- Burial Sites Monitoring
- Peacekeeping

Sensor Usage: The following paragraphs describe the Predator sensors and their utilization during deployment.

Daylight TV Cameras include a color TV camera with a continuous 16-160 mm zoom capability and another identical color TV camera with a fixed 955 mm spotter lens. The color motion video produced by these sensors is the most intuitive intelligence product and is the product of choice by most of the operational commanders. The value of the motion video is obvious for tracking moving targets of interest but it was also the first choice for observing stationary targets. Additionally, although the intelligence community has long preferred black and white imagery, the color product is the product of choice for operational commanders and has proven to have value in recognizing earth that had been disturbed, in rapidly identifying the blue NATO vehicles, and other applications. The daylight TV cameras are only marginally useful at night and only in a relatively well lit environment.

The Forward-looking Infrared Camera produces the same motion video but without color. It is the sensor of choice in darkness or visibility conditions that reduce the effectiveness of the daylight TV cameras. The FLIR sensor is equipped with three fields of view, 11 mm, 70 mm, and 280 mm, and is equipped with a 2X doubler that can be applied to each field of view. Unfortunately, the sensitivity of the Platinum Silicide (PtSi) detector would only support the use of the doubler against "hot" targets. This problem has been addressed and will be explained later.

The Synthetic Aperture Radar (SAR), first used in the second deployment, produces imagery that are the least intuitive in that it is still images only, the images are monochromatic, and present an "unfamiliar" look. Trained SAR analysts must view SAR images. Therefore, operational commanders would select SAR as a last option only when weather conditions made the other sensors ineffective. Trained analysts actually liked the Predator SAR product.

Mission Effectiveness: The tables below indicate the continual improvement in mission effectiveness over the four years of deployment in support of the Bosnian operations.

Flight Hours

	year	total	mission	%
Nomad Vigil	1995	850.1	756.3	89%
Nomad Endeavor	1996	1444.0	1351.2	94%
Joint Guard I	1997	1482.5	1432.8	97%
Joint Guard II	1998	867.9	831.9	96%

Flights

	year	total	mission	%
Nomad Vigil	1995	130	79	61%
Nomad	1996	253	167	66%
Joint Guard I	1997	211	156	74%
Joint Guard II	1998	131	100	76%

Of the missions attempted, approximately 70% were completed with 20% aborted due to weather and 10% due to other factors. It is important to note, however, that many of the aborted missions were partially complete since intelligence was successfully collected on one or more targets prior to the abort. The majority of the weather aborts occurred during the severe winter months in central Europe where icing conditions are prevalent. With the "all weather" SAR sensor aboard, it became apparent that the Predator would have to be modified to be able to withstand the rigors of winter weather. This will be discussed later.

Lessons Learned / Changes Made: The remarkable new capability provided by the Predator surveillance and reconnaissance system brought about a number of changes in the way that the operational and intelligence organizations do business. The result was an evolution in organizational relationships, tactics, doctrine, methods and overall battlefield management that remains one of the most profound aspects of the Bosnian operations.

With the original concept of operations, the only intended product of the Predator system was still images and textual reports to be distributed only to the intelligence analysis facility at JTF headquarters. Through the experience of the Bosnian operations, several user classes emerged. The availability of narrated motion video has generated a new set of users with operational commanders and their personnel choosing to view the motion imagery rather than waiting for still imagery and intelligence briefings.

At the beginning of the first deployment, the standard cycle for the Air Tasking Order was 72 hours. That is the time from initial receipt of intelligence requests to the time that the intelligence platform was collecting intelligence over those targets was an average of 72 hours. This time decreased to 48 hours and continued to decrease until retasking during the mission became the norm. As imagery is collected early in a mission, delivered rapidly to the users and analyzed, often the mission target assignments were changed to increase time over some targets, add new targets and delete other targets. Some of the commanders found that by being in direct communication with the payload operator in the GCS, that they could instantly retask the Predator. This phenomenon could lead to direct remote control of the payload.

The reliance of commanders on the real-time video has tended to erode the traditional role of the intelligence analyst. The commanders have noted, however, that they can misinterpret or be misled by what they see (i.e. they are more likely to be diverted by a decoy than a trained analyst). Additionally, the trained analyst is more inclined to want more in-depth information and more trend information on a target than the commander. Consequently, there is an ongoing realignment in the traditional roles and responsibilities as the forces learn to maximize the benefit of this new "virtual presence" in the battlefield that the Predator provides.

System Improvements: There have been a number of improvements to the Predator that resulted directly from the deployed experiences. These include:

- Improved system support
- Improved digitization and compression for the Ku band satellite data link.
- Enhancements to Mission Planner and Flight software.
- Improvements to the IR sensors
- Development of a de-icing system.

De-icing system –

The laminar flow wing on Predator which allows the aircraft to have extremely long endurance is extremely susceptible to the disruption of airflow as would be introduced by the accumulation of even small to moderate ice on the wings. In order to cope with the rigors of winter weather in Central Europe, a de-icing system was developed for Predator. After considering several alternatives, the resulting design contained the following elements:

- heated camera lens
- heated pitot/static system
- ice sensor
- "weeping wing" method of distributing an ethyl glycol mixture over the wing and tail surfaces to prevent / remove the accumulation of ice.
- The addition of a turbo-charged engine to offset the additional weight and loss of lift associated with the de-ice equipment.

Improved IR sensor –

The limitations of the use of the 2X doubler lens with the existing Platinum Silicide (PtSi) detector on the FLIR sensor caused a search for a new sensor. The sensor has been replaced with a new sensor that uses an Indium Antimonide (InSb) detector that is approximately ten times more sensitive than the PtSi detector. Although the new InSb detector is half the size of the PtSi detector (256X256 vs. 512X512), the significant increase in MRTD sensitivity has made the 2X doubler lens a valuable asset. Resolution and image interpretation improvements are dramatic.

ATC Voice Relay –

As the mission environment in Bosnia transitioned from wartime to peacekeeping, the concerns about integrating the Predator unmanned aircraft into the mix of commercial and military air traffic increased. One of the major limitations of unmanned air vehicles is that communications with air controllers was accomplished over the telephone to controllers who were often a great distance from the GCS site rather than a manned aircraft whose pilot communicates directly via radio with the local controller. The solution was to incorporate a voice relay system in the aircraft that allows the pilot in the GCS to use the standard "push to talk" method of communication to talk directly to controllers in the area where the aircraft is operating. The system uses the Ku band satellite data link to relay the communications from the radio in the aircraft to the pilot in the GCS.

Mode IV IFF –

Also to enhance the ability to integrate Predator into the mix of commercial and military air traffic, a standard military Mode IV IFF system is being integrated into the Predator system.

Sensor Upgrade –

The optical sensors are also being upgraded with autofocus and autotrack features.

Summary: As the U.S. government continues to gain deployed experience with the Predator system, there has been on ongoing evolution in the way the battlefield is managed. Additionally, there is a new awareness of requirements to make this and future systems more responsive to the needs of the operational commanders. As new system requirements have been identified for Predator, General Atomics Aeronautical Systems, Inc. has been able to meet customer needs.

Short Range Reconnaissance
The LUNA Experimental UAV Program

(April 1999)

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1. SUMMARY

This paper reports on the background, the performance requirements, technical characteristics, special program features and lessons learned from the LUNA Experimental UAV Program.
This program is being funded by the R&D Program of the Bundeswehr. This 18 month effort will be finalized by phase 2 field trials in may/june 1999. Main goals to be proven are, reconnaissance performance in an operational environment and easy handling i.e. mission planning, mission conduct and maintenance.
The lessons learned from LUNA so far can be applied to other programs - already today, but also particularly in the future.

2. Introduction

LUNA is an acronym and stands for "Luftgestützte unbemannte Nahaufklärungsausstattung", which means in English "Airborne Unmanned Close Range Reconnaissance System". LUNA is a pure pre-phase activity and originates from an initiative of the Armored Reconnaissance Corps from the year 1990. The basic idea was to equip the armored reconnaissance units beyond the FLOT with an airborne means of reconnaissance that is easy to operate. This should both improve the self-protection capability and increase the units' effectiveness.
In 1996, the BWB conducted an international competition in which eight competitors from different countries presented their solutions. The selection of the contractor had been based on a careful assessment in accordance with recognized standards.
The study contract for the development and testing of the LUNA X-2000 functional model was signed on 10 October 1997 with the Contractor EMT. After 18 months this contract is now about to expire.
In about 2 to 3 months it will be completed with phase 2 of the field tests.

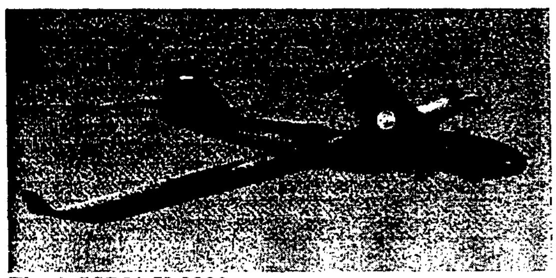

Fig. 1: LUNA X-2000

So far, four aerial vehicles have been built and certified for military use under this R&D contract.

3. Performance Requirements

The system requirements were already defined in such detail that due to their nature and content they largely fulfilled the requirements of a development specification.

The LUNA requirements specification stipulated the following targets:

- use of commercial-off-the-shelf components, where possible,
- takeoff weight approximately 20 kg,
- minimum operating range of 10 km,
  minimum data link range of 20 km,
- very simple operation, automatic flight control; operation by two persons, aeronaticall skills not required,
- real-time E/O and IR images via data link,
- detection, recognition, identification and location of individual wheeled and tracked vehicles,

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

even if equipped with signature-reducing camouflage, by day and night and in bad weather,
- integration/transport in the rear hold of an armored reconnaissance vehicle or small road vehicle.

4. Technical Characteristics

In summary one can say that the original program expectations for LUNA X-2000 were far exceeded in terms of schedule and technology.

4.1. Takeoff and Landing

Investigations to determine the optimum launch and recovery procedure led to the design of a foldable bungee catapult. It takes a 4 meters rail to accelerate the UAV to about 70 km/h, well beyond liftoff speed. For landing, a special parachute is being used. The released parachute turns the airframe over in a backwards position in order to protect the payload. The sink rate is about 4 m/s. The touchdown is dampened by mechanical shock absorbers due to the high elasticity of the airframe.

4.1. Airframe, Propulsion, Signatures

The required takeoff weight, payload and endurance could only be achieved by a very economic use of propulsion power.
The aerial vehicle was therefore designed as a high-performance powered glider.
It has a maximum speed of 160 km/h; at cruising speed, i.e. 70 km/h, it only needs 0.75 kW of its nominal propulsion power of approximately 6 kW.

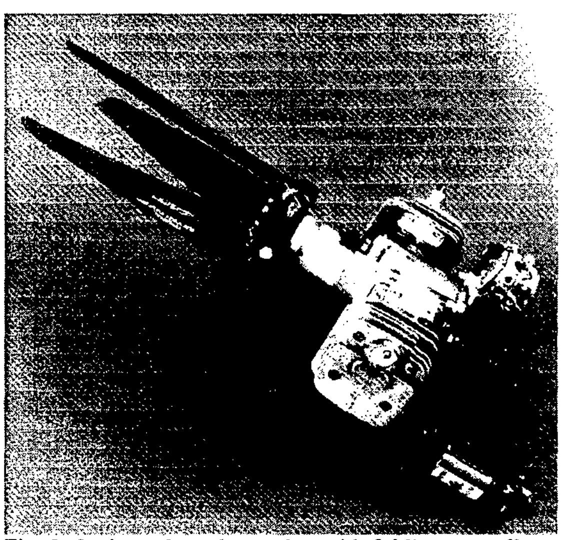

Fig. 2: 2-piston 2 stroke engine with folding propeller

This is less than the thermal power loss of other tactical drone systems and, of course, results in considerably better signature characteristics.

The engine can be randomly switched off and restarted during flight.
In unpowered mode the LUNA X-2000 has a glide ratio of 1:18; over a distance of 18 km the vehicle loses about 1000 m in altitude.
The resulting operational advantages will have to be investigated in detail yet.

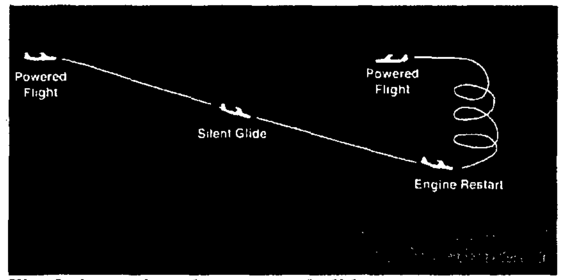

Fig. 3: intermittend unpowered glide

The endurance time in the target area can presumably be doubled, and the acoustic and IR signatures will be further improved.
Due to the fiber glass design, additional measures to reduce the LUNA X-2000 radar signature will not be necessary. It can be assumed that the contracted laboratory measurements will yield a value that meets the requirements for a larger drone with stealth characteristics.

4.2. Sensors

Undoubtedly, the central aspect is the reconnaissance performance of the system.
LUNA X-2000 is among the top players and can compare with any other system.

The miniaturized sensor module with its weight of about 2.1 kg currently contains an analog daylight color video zoom camera and a digital thermal imaging camera. Alternatively, each one of these cameras can be coupled with a digital still image camera with internal image storage. The payload is installed in a gimbal system and can be continuously tilted by 45° in any direction from the ground control station.

With its multiple sensors LUNA X-2000 meets the requirement for detecting, recognizing, locating and unambiguously identifying individual tracked or wheeled vehicles (up to 0.5 tons).
At the moment and in the foreseeable future, no other airborne reconnaissance system comparable in size and takeoff weight can fulfill these requirements.

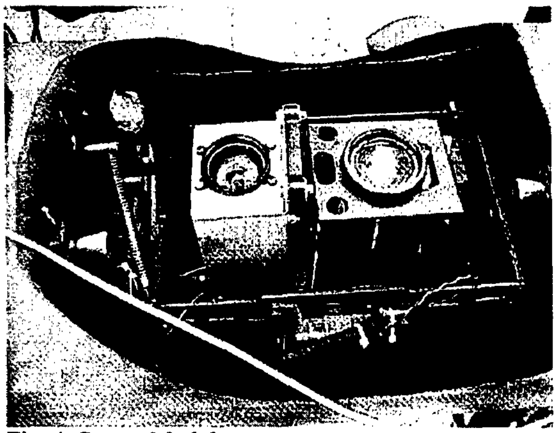

Fig. 4: Sensor Module

In addition, the drone is equipped with a nose mounted color video camera which provides the operator with a permanent view of the airspace along the flight path (clouds/weather) and of the reconnaissance area lying ahead.

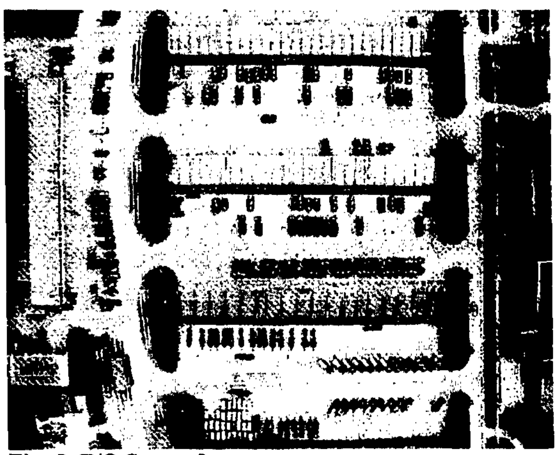

Fig. 5: E/O Sensor Image

4.3. Data Link

For real-time transmission of the sensor data collected the LUNA X-2000 system uses a microwave data link in the 4.4 to 5.0 GHz carrier frequency band which is rather beneficial in terms of atmospheric attenuation.

Two modes are available, 5 MHz bandwidth analog and 10.7 Mbit/s digital.

In order to improve the interference resistance of the radio relay link, both modes use data scrambling. In digital mode a continuous 8 bit checksum check and frequency hopping are performed.

On radio contact loss an automatic re-contacting procedure is being pursued.

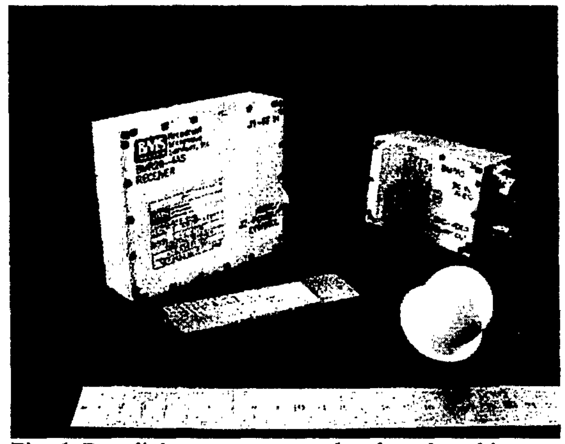

Fig. 6: Data link components and on board tracking Antenna

The data link is equipped with a power management; maximum antenna output is 3 Watt. For the time being a datalink range of 22 km has been demonstrated. During the concluding 2nd phase of the field tests in May/June this year, EMT will employ an improved data link with a range of 65 km which has been adapted to the LUNA X-2000.

Successful ground tests were already performed by the U.S. supplier, the hardware has been ordered and delivery is in process.

4.4. Flight Control System (FCS)

The LUNA X-2000 flight control system is miniaturized and fully digitized. Its capabilities and performance are equal to those of manned aircraft.

The on-board equipment comprises an attitude gyro, a magnetic compass, rate of turn sensors, air data sensors and accelerometers.

Basic navigation is supported by SATCOM differential GPS. Up to a distance of 20 km from a reference station (usually the ground control station) this provides for navigation and detection accuracies with a remarkable CEP of about 10 m.

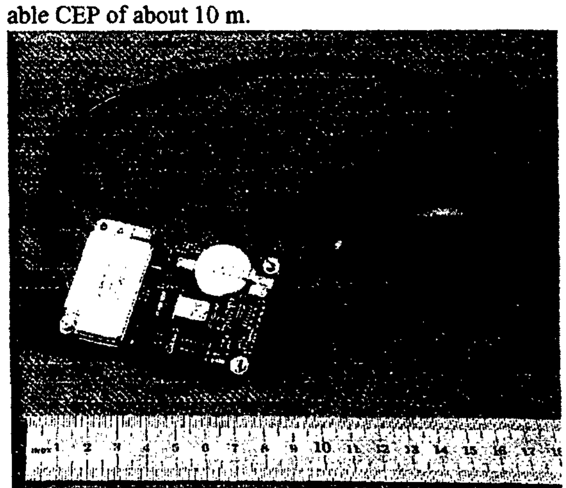

Fig. 7: Differential GPS Module with Antenna

4.5. Man-Machine Interface

In consultation with the purchaser and the user, the human engineering concept for the LUNA X-2000 operation was repeatedly streamlined in several iterative steps to integrate automatic processes.
By now the device is extremely easy to handle. The System can be operated by 2 persons. Turn around time is less than 15 minutes. As a matter of fact, armored reconnaissance corps soldiers without any special training were able to effectively operate the system after only a few hours of familiarization.

4.6. Ground Control Station

The ground control station is equipped with two screens, one for the aerial and video images taken, the second one for displaying a map with the flight path and a IFR-type virtual cockpit. The map presentations are based on the Bundeswehr standard digital 3-D maps of the Bundeswehr Geographic Office; that is an essential element of mission planning. The 3-dimensinal digital map shows the air vehicle position, the camera footprint and flight path. To facilitate image interpretation and operator orientation, the images are north referenced in real time.

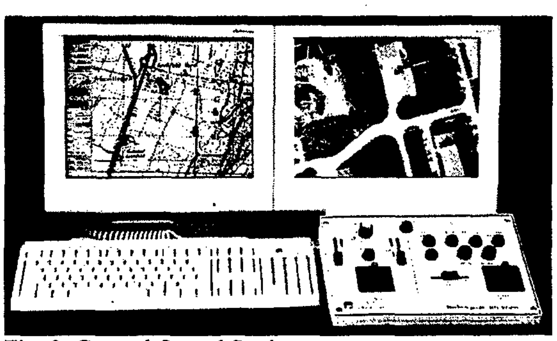

Fig. 8: Ground Contol Station

4.7. Mission Planning

Mission planning is performed within a few minutes by mouse or keyboard entry of a list of waypoints. The mission planning software checks the data entered for plausibility and feasibility, particularly with respect to obstacle avoidance, shading and range. The software issues error warnings and proposes corrections. The fully automatic mission – from launch to automatic recovery – is preprogrammed by a sequence of waypoints. The anticipated landing position does not necessarily have to identical with the takeoff position. It is possible to transmit sensor data to another ground control station and to transfer control of the aerial vehicle to another station.
For post-flight analyses and for training purposes the systrem allows complete mission playback including sensor data, map display and virtual cockpit.

4.8. Special Program Features

- Already at contract conclusion, the parties to the contract were aware of the fact that a dual-use product would be developed. The company had to aim at producing a marketable and competitive product. This requirement was met by EMT. Using own resources, they realized improvements beyond their contractual obligations.

- The contractor successfully managed to implement the capabilities required from this unmanned reconnaissance system with a minimum effort. The scope of the system was consistently kept small. This results in a reduced complexity and, of course, cost savings for future procurement and use.

- The Bundeswehr material development cycle calls for the use of commercial-off-the-shelf materiel and readily available components as a standard solution. New developments shall be the exception to the rule. Therefore, COTS materiel and components were used, wherever possible. To avoid making compromises, however, only such COTS parts were selected which proved to be absolutely suitable due to their function, performance, reliability, price, availability, and competitiveness.
Due to the consistent use of sophisticated commercial materiel and components the time required up to the functional model tests was extremely short.

- No major technical problems arose during the life of the contract. Since contract conclusion approximately 18 months ago about 90 flights have been performed - under icing conditions, with flight altitudes above 3000 m, under bad weather conditions, and with up to 5 flights per day with only one vehicle. The statistics show a technical availability of more than 98 %, no equipment losses, and no damage that would have required third or fourth echelon maintenance actions. These results are unmatched in the field of UAVs, at least as far as the Bundeswehr is concerned.

- As of today, the system can already be considered to be marketable and commercial. It has been granted a preliminary certification a category 2 certification for flights over thinly populated area is envisaged by the Bundeswehr authorities.
The certification of functional readiness and operational safety has been required by the Intelligence and Reconnaissance Study Group it should be issued timely to phase 2 field trials.

5. Summary and lessons learned

Small system size, performance, reliability, ease of handling, procurement and life cycle costs make LUNA X-2000 to fit the acutal Bundeswehr needs.

Based on the degree of maturity achieved within that 18 month contract, from today's technical and contractual point it is considered possible to have the first operable system delivered in a 6-8 months timeframe.

Competition is most valuable to increase contractor performance and to decrease costs in government funded R&D programs.

Extended implementation of 1st choice COTS items is considered a key element to reduce the overall development risk to cut program costs and to concentrate resources on areas of high interest.

Teamwork and ingenuity seam to be more beneficial to the success of a program than outsourcing and shareholder value.

UCAV CONCEPTS FOR CAS

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SUMMARY

A system concept is described that would give individual combat users access to and (limited) control of a network of unmanned air vehicles. Applications would be both lethal and nonlethal. In the nonlethal form, unmanned combat air vehicles could respond to fire support requests as if they were the virtual equivalent of organic, long-range artillery. In the nonlethal form, unmanned reconnaissance air vehicles could point their sensors at locations and/or areas of interest and respond with target imagery or coordinates of selected target types. Capabilities currently exist to evaluate these concepts in simulated or actual field trials and/or to develop an initial operating capability (IOC).

NOTATION

CAP - combat air patrol
CAS - close air support
CITS - CAS Integrated Targeting System
CONOPS - concepts of operation
COTS - commercial off-the-shelf
FO – forward observer
GOTS - government off-the-shelf
GPS – global positioning system
IOC - initial operating capability
IPT - integrated product team
ISR - intelligence, surveillance, and reconnaissance
LM - Lockheed Martin
LMTAS - Lockheed Martin Tactical Aircraft Systems
SOW - standoff weapon
TACP - tactical air control party
TCS - Tactical Control System
UAV - unmanned air vehicle
UCAV - unmanned or uninhabited combat air vehicle
URAV - unmanned reconnaissance air vehicle
USAF - United States Air Force
USMC - United States Marine Corps

1. INTRODUCTION

For many years an uneasy relationship has existed between advocates of manned and unmanned air vehicles (UAVs). Manned aircraft advocates recognize UAVs as an inevitable element of the future tactical air environment, but also see them as competitors for missions and resources. Unmanned system advocates, on the other hand, tout the potential synergy between manned and unmanned air operations but praise their concepts as *alternatives* to the high cost and risk of manned systems.

At Lockheed Martin Tactical Aircraft Systems (LMTAS), the unmanned combat air vehicle (UCAV) integrated product team (IPT) has advocated a mix of manned and unmanned systems, but it has not been easy to articulate exactly how this will work[1]. However, recent technical and operational developments, including employment of Lockheed Martin (LM) Close Air Support (CAS) Integrated Targeting Systems (CITS, also known as LM "Sure Strike" Systems), have suggested new ways of employing UAVs and UCAVs to support ground operations.

The CITs Sure Strike System, developed and patented by LMTAS, is operational with U.S. Air Force (USAF) units deployed to support operations in Bosnia/Yugoslavia. This system enables the operator to determine GPS coordinates by aiming it at a desired target. The system then transmits GPS data and other pertinent information directly to CAS aircraft. Currently, this streamlined CAS targeting and digital communication system is interoperable with F-16 units based at Aviano, Italy.

Extending Sure Strike capability to be interoperable with other manned and future UCAVs could be readily accomplished. Further, combining this type of system with GPS-aided weaponry would allow many different types of combat aircraft (including UCAVs) to effectively attack targets from higher altitudes—and in all-weather conditions—under the control of a local forward observer (FO). In essence, the aircraft would function as the virtual equivalent of long-range organic artillery. Extending this basic concept to that of putting sensors "on target" could allow FO direct control of UCAV and UAV sensors and line-of-sight receipt of images. As the system concept unfolds, it becomes clear that the end result is a potential *network* of UAVs and UCAVs capable of providing reconnaissance and/or fire support for any validated user.

1.1 Unmanned Air Vehicles

The term "UAV" describes a variety of unmanned air vehicle types ranging from what are essentially militarized radio-controlled tactical models to large, sophisticated sensor platforms that fly theater-level intelligence, surveillance, and reconnaissance (ISR) missions. Many other UAV types are also being developed and/or considered that cover an even wider range of sizes and missions. At one extreme are micro-UAVs, carried and launched by individual soldiers, for use on "close-in" missions that range from reconnaissance and

Paper presented at the RTO SCI Symposium on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles", held in Ankara, Turkey, 26-28 April 1999 and published in RTO MP-44.

intelligence-gathering to surgical strike. At the other end are UCAV, whose primary purpose is air-to-ground strike against targets which, for any number of reasons, are assigned to unmanned, instead of manned, aircraft. Finally, there is another class of vehicles not normally considered UAVs that perform unmanned air-to-ground strike missions—cruise missiles and air-launched standoff weapons (SOWs). Technically, these systems have all of the characteristics of traditional UAVs except in their early phases of flight (boost-launched and/or carried as payload) and their terminal phases—they fly one way to the target and are not recoverable. Otherwise, they can perform many of the functions of other UAVs, which include flying ISR, electronic warfare (EW), and strike missions. For the purpose of this paper, therefore, UAVs will be considered to fall into four basic UAV types (Figure 1): URAV, TUAV, UCAV, and SOW.

1.1.1 Unmanned Reconnaissance Air Vehicles (URAVs)

The distinguishing characteristic of this UAV type is its intended use—support of high-level decision makers (theater commanders, their staffs, and planners) with timely ISR. The need for timely information at these levels is nearly insatiable, and even though lower level users can request support, experience has shown that they do not fare well in comparison. Interestingly, the problem is often not the availability of information, but rather its processing and dissemination. ISR information processing and distribution is a traditional intelligence function, one that has a hard time keeping up with demands from higher command levels. Lower level commanders and their staffs, therefore, have started to demand better access via another type of UAV.

1.1.2 Tactical Unmanned Air Vehicles (TUAVs)

TUAVs perform a URAV-like function for lower levels of the command structure, down to and including individual fighting units. For definition purposes we include micro-UAVs, which drive the customer base down to the individual soldier, sailor, airman, or marine. Experience with TUAVs in combat and exercises has shown them to be extremely valuable for the commander who has them and detrimental for those who do not. As a consequence, we can expect them to have high user demand (and be high-value targets for enemy forces). Like URAVs, the demand for timely analysis and information dissemination can be a limiting factor for product users.

1.1.3 Unmanned Combat Air Vehicles (UCAVs)

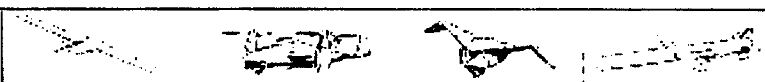
UCAVs are a relatively new type of UAV whose primary function is to deliver ordnance. Near-term capability ranges from preplanned strikes against fixed ground targets to suppression of enemy air defenses (SEAD). Longer term capabilities cover a full range of missions including carriage of new weapon types that are uniquely suited to the UCAV concept[3]. Most projected applications are driven by relatively traditional manned and unmanned concepts of operation (CONOPS). Some authors, however, have proposed unique new applications such as support of ground maneuver units under the control of forward ground elements[1].

1.1.4 Standoff Weapons (SOWs)

Given their publicity in recent air combat operations, SOWs need little introduction. This paper, however, will more broadly define a SOW as any precision-guided weapon that allows friendly forces to stand off from the enemy and to precisely put ordnance on target. Even though SOWs are included in this paper as unmanned vehicles, employment concepts are generally driven by their launch platforms. Therefore, SOWs will not be addressed separately, but rather as elements of other platforms.

1.2 Close Air Support (CAS)

CAS can have different meanings. For the purpose of this paper, CAS is defined as any mission involving aerial delivery of weapons in direct support of, or in close proximity to, friendly ground forces. Basically, it is a mission that requires extremely close coordination between air and ground elements to ensure that weapons are accurately placed on enemy positions. These types of missions involve strict rules of engagement and require unambiguous ground coordination and/or control *prior* to weapon release.



	URAV	TUAV	UCAV	SOW
• Mission	Recce (Primary)	Recce (Primary)	Strike (Primary)	Strike (Primary)
• Speed	L-M	L	M-H	L-H
• Maneuverability	L	L-M	M-H	M-H
• Altitude	M-H	L	L-M M-H	L-M M-H
• Observables	M-L	M-L	L	M-L
• Payload	500 - 2000 lb	< 500 lb	500 - 4000 lb	< 4000 lb
• Sensors	RF / EO / IR	EO / IR	RF / EO / IR	Targeting
• Bandwidth	H	M-H	L-M or H	L
• Endurance	Days - Weeks	Hours	Hours - Days	Hours

L – Low M – Medium H – High

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Figure 1. Unmanned Air Vehicle Types

1.2.1 Air-Ground Coordination

One reason for the complexity of the CAS mission is that it involves two individuals, one in the air and one on the ground. Both have to be convinced that other understands the tactical situation, the deployment of friendlies, the threats, and the precise location of the intended target. Each may have a unique level of understanding and will have to rely on communications to convey that knowledge to the other. Adding to the complexity of the situation is the traditional reliance on voice communications and its inherent potential for misunderstanding and mistakes.

Although each party will share a common tactical objective, each will have individual concerns and motivations. The person in the air will be concerned about getting shot down and will want to minimize aircraft exposure. The person on the ground will be concerned about the potential for weapons falling on him/her or his/her troops and will want to minimize the potential for error. The two parties also operate in very different environments and see events unfolding at different speeds. As a consequence, the time required for them to achieve a sufficient level of understanding to allow weapon release can be significant, 20 minutes or more from aircraft arrival to weapon release if in a restrictive environment. Fortunately, technology has improved this situation, especially GPS, common reference digital maps, and air-ground datalinks.

1.2.2 CAS Integrated Targeting System (CITS)

State-of-the-art technology has revolutionized communication and coordination for CAS operations. Although a number of systems are under development, only one has been deployed—the USAF/Lockheed Martin patented Sure Strike CITS. The USAF CONOPS for CAS (Figure 2) assigns coordination responsibility to a ground-based tactical air control party (TACP) manned by USAF personnel. Sure Strike provides the TACP with a man-portable system that interfaces with F-16 Block 40 aircraft via an improved data modem (IDM), low bandwidth datalink. The Sure Strike system (Figure 3) integrates many commercial off-the-shelf (COTS) and government off-the-shelf (GOTS) systems, which allow the TACP to quickly and precisely geo-locate enemy ground targets and digitally transmit them as GPS target coordinates *directly* to the F-16 by means of a standard "9-Line" digital message.

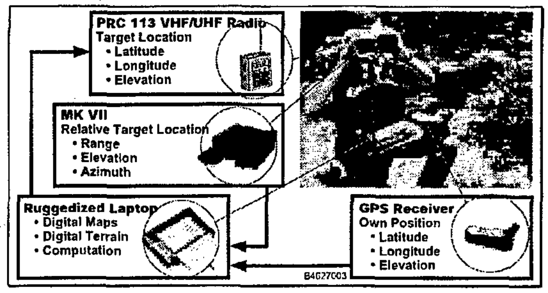

Figure 3. LM Sure Strike Ground Station

1.2.3 F-16 Interface

Upon receipt of the Sure Strike CITS message by the F-16, the pilot receives a heads-up display (HUD) indication while the target GPS coordinates are automatically passed to the F-16's Fire Control Computer (Figure 4). Sensors and weapons are aimed at the target, allowing the pilot to quickly acquire and confirm it with the TACP. The final step is the attack, which is executed by the pilot with the concurrence of the TACP. Although

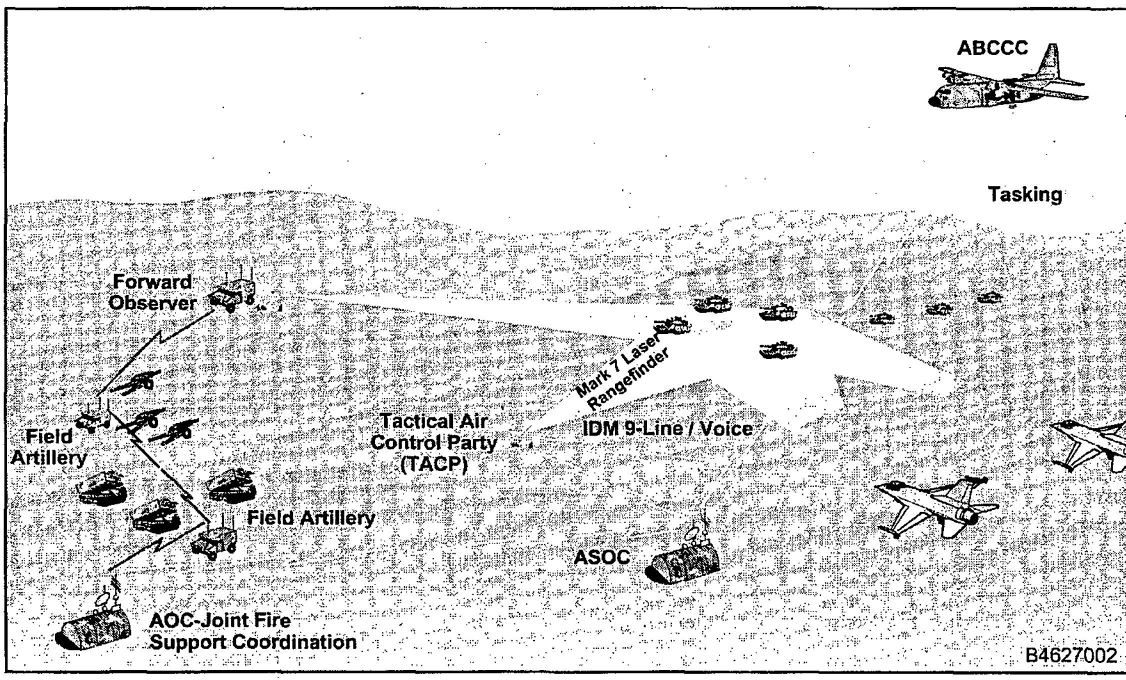

Figure 2. F-16 Sure Strike CONOPS

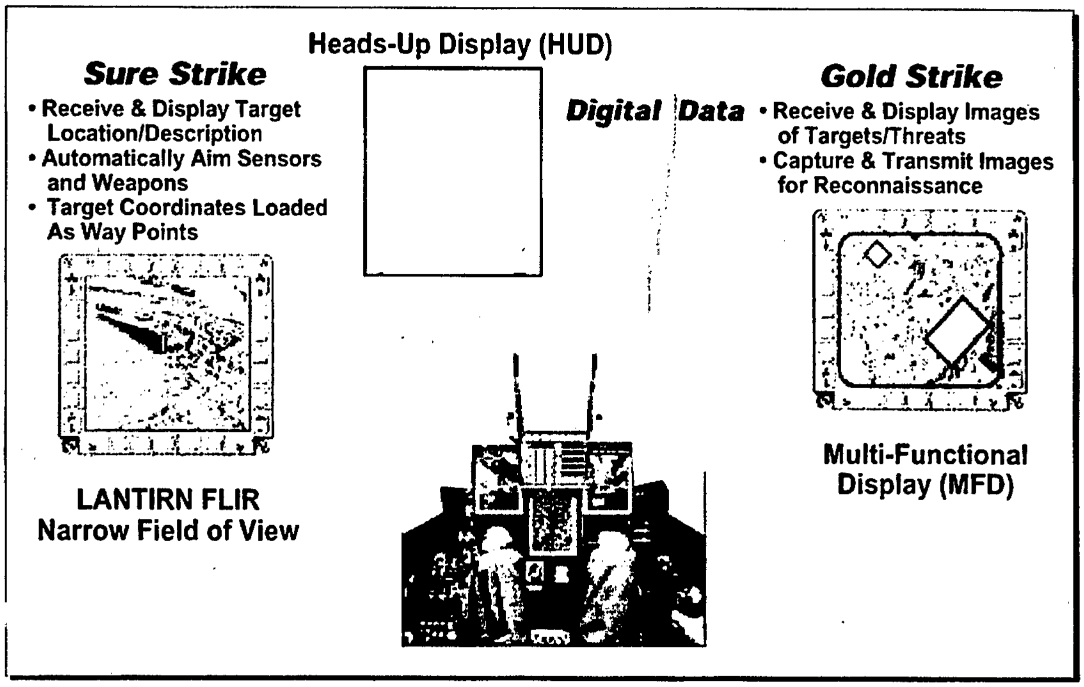

Figure 4. F-16 CAS Information in the Cockpit

little more than a straightforward adaptation of existing CONOPS and technology, Sure Strike has reduced CAS coordination and communication times by an order of magnitude.

1.2.4 "Gold Strike" Enhancement

Currently developed but not deployed is the enhanced LM "Gold Strike" CITS, which adds digital imagery capability to Sure Strike transmissions. This allows the TACP to uplink a digital situation awareness map to the pilot and/or to receive air vehicle sensor images on the ground (Figure 5). Although not originally intended for this purpose, Gold Strike allows any appropriately equipped air vehicle to be tasked for and to disseminate sensor images to other combat users in the air and on the ground. This function is performed using existing tactical radios since the IDM is a modem, not a separate datalink. This inherent capability sparked the idea of adapting the Gold Strike concept to local tasking and reception of tactical and reconnaissance UAV sensor products.

2. OPERATIONAL CONCEPTS

Although intended to bring revolutionary new capabilities to the battlefield, in essence, UAVs have entered the force as relatively straightforward unmanned equivalents of manned aircraft. However, experiments are underway to develop UAV-unique operation and control concepts. These experiments should transition to not only new operation and control concepts, but also to new concepts for ISR product analysis and dissemination. If they do not, future UAV effectiveness will be constrained, and overall force effectiveness will be impacted accordingly.

2.1 Manned Air Operations

For sound operational and tactical reasons, manned aircraft tactics and operation and control concepts have relied on pilots to exercise individual initiative and to be the final decision authority for himself and his aircraft and/or flight of aircraft. The tactical air battle is fast-paced, and the pilot's position in the middle

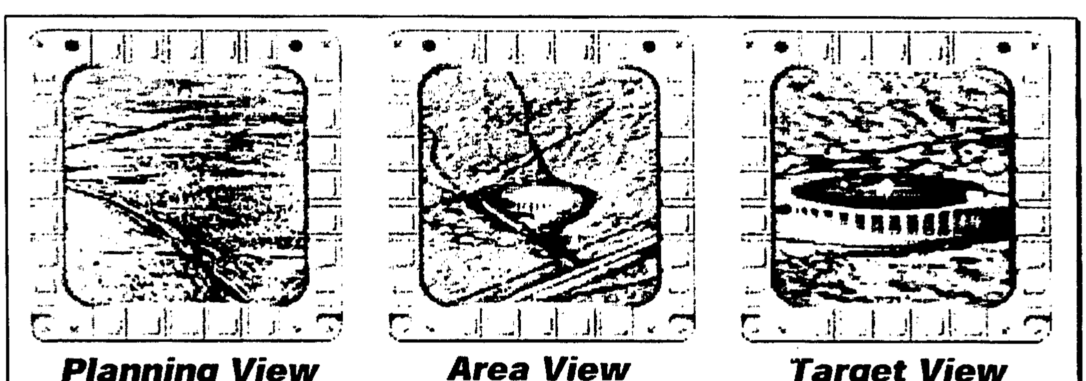

Figure 5. LM Gold Strike Imagery

of, or above, the fray usually puts him in the best position to make tactical decisions. As the tactical air environment has become more complicated (and crowded) it has become necessary to better coordinate among aircraft. Hence, the concept of air controllers developed. Regardless of the title, the job of the controllers is to coordinate, and individual pilots and/or flight leaders retain the ultimate control authority.

2.2 Unmanned Air Operations

From lessons learned over decades of manned aircraft operation, it is logical to assume that UAV operators should have an air vehicle command function comparable to their manned aircraft counterparts. In fact, early UAV operators were remote pilots and had "stick and rudder" control over their air vehicles. Today they exercise a higher level of control, more comparable to a mission manager, but UAV operators still retain traditional pilot-in-command authority. This, however, may not always be the best control concept. The U.S. Army, for example, is developing a capability for a Hunter UAV to be controlled from the cockpit of an Apache helicopter[4]. In this application, the Hunter functions as an extension of onboard Apache sensors. Clearly a ground-based operator, in this situation, would be ill-suited to exercise control over the UAV. Instead, he will hand off control to the Apache for a period of time and take it back when the Apache no longer needs it. During this period of time, the ground-based operator presumably would monitor the UAV and reassume control if necessary.

The U.S. Navy has conducted similar experiments in which Predator UAV control has been passed among multiple users to include submarines. UAVs have also been "forward passed" to Marine ground units. If development of these UAV operation and control concepts continues, the traditional pilot-in-command concept will be quite different from manned aircraft.

2.3 Other Manned Influences

Manned aircraft operation and control concepts also influence other UAV operations. For example, manned ISR aircraft typically separate the functions of aircraft control, sensor management, and data analysis and dissemination. To allow the pilot to concentrate on flying the aircraft, a second operator, sometimes on the ground, controls the sensors. Information processing and dissemination is separated because it is an air intelligence function and involves separate skills, clearances, and organizational responsibilities.

Even though UAV operator workloads and environments are different, the same approach is used. One UAV controller usually is responsible for flight path management, and another has responsibility for sensor management and control. Sometimes a separate station is used for launch and recovery and another for mission planning and replanning. Yet another station (often a separate van) processes and disseminates the data. This approach can result in UAV operator-to-air-vehicle staffing ratios that far exceed those of manned aircraft.

3. PROJECTED CONSTRAINTS

Current concepts of UAV operation, control, and information distribution are based on operational models originally developed to support limited numbers of users with predefined requirements and needs. All indications are that the demand for UAV support products will continue to increase. What is not clear, however, is whether constraints imposed by traditional UAV concepts of operation and control will be able to keep up with the potentially explosive growth in user demand.

3.1 ISR

URAVs primarily support theater commander and planning staff needs. Missions are scheduled well in advance to meet staff and intelligence needs, and product dissemination is planned accordingly. Ad hoc demands from lower level users, therefore, are difficult to accommodate. The challenge is not only planning and collection for multiple users, it is also information analysis and dissemination. There often simply are not enough available intelligence analysts to meet the time-critical needs of larger numbers of tactical users.

3.2 Tactical Reconnaissance

TUAVs probably will have the same constraints as URAVs, except they will occur at lower levels—ad hoc demands from lower unit level users may prove difficult to accommodate. Once again, the problem may be available manpower. TUAV operators and information specialists will be focused on supporting their primary users, and other demands will be prioritized accordingly.

3.3 Weapon Delivery

UCAV CONOPS are still in the experimental stages of development, but current trends are to plan and execute their missions like manned aircraft. Targets and/or support missions will be planned in advance, and UCAV operators will function like strike package managers. Once again, ad hoc requirements from lower levels of the organization may be difficult to accommodate.

3.4 Multiple Users

The more capability UAVs bring to the battlefield, the more people will want to use them. Although technology can help resolve some constraints, e.g., application of state-of-the-art flight path and sensor automation technology to reduce UAV manpower, it will not provide a complete solution. Fundamental CONOPS changes will be required to resolve inherent constraints in traditional operation and control concepts to meet time-critical demands of larger numbers of increasingly demanding combat users.

4. ALTERNATE COTS-BASED "CONOPS"

There are many well-developed commercial operation and control concepts that could meet future multiuser demands for timely combat air support. They are applicable to UAV and UCAV operation and control concepts and ISR information processing and dissemination.

4.1 Internet

Internet-like, database concepts have well-recognized capabilities to meet multiuser demands for timely information. Included are near-real time, dynamic database approaches that can meet many ISR needs (e.g., time-annotated imagery retrieval by users with appropriate security access codes)[5]. In situations where database products will not meet combat information needs, other approaches can be considered.

4.2 Delivery Services

The consumer service industry is replete with operation and control concepts that efficiently respond to time-critical, multiuser demands. A tongue-in-cheek example is pizza delivery, which operates on the fundamental premise of a universally available command and control system (a phone and a credit card), an agreed-upon list of available products (a menu), and a quick response delivery system. A more sophisticated example is automated taxi dispatch. Customer service requests (pick up time and location) go directly into a time-sequenced database that is digitally transmitted to potential providers (subscribing taxi drivers) based on their last reported location. The first driver to respond (by screen touch) gets the fare and assumes responsibility for meeting the user requirement. Similar concepts have been envisioned for military applications such as sensor-to-shooter pairing.

5. ARTILLERY-BASED CONOPS

Field artillery has a well-developed concept of operation and control that could be adapted to meet multiuser, time-critical UAV and UCAV support requirements. Artillery must not only support a large number of users located all over the battlefield, but it also has to meet stringent response-time requirements. Since it performs a CAS-like function, the discussion will start by comparing the two. Nonlethal applications that are based on this same concept will be addressed in subsequent sections.

5.1 Tasking and Coordination

Both artillery and CAS collocate trained specialists (forward observers and forward air controllers) with ground units to direct and coordinate support. There are, however, differences. Forward observers are usually "organic" to ground maneuver units, while FACs function at the interface of the air and ground forces.

5.2 Targeting

Forward observers task gun crews for fire support using map coordinates. The gun crew responds with a round calculated to hit the target. Using plus/minus corrections, a forward observer directs subsequent rounds onto the target and finally gives authority to "fire for effect." A FAC, on the other hand, uses ground features to orient the pilot about locations of friendly forces, enemy forces, and potential threats. The reason for visual features vice map references is that air and ground forces use different maps and map references. A forward observer uses a map with features and symbols optimized for ground operations, and the map will be annotated with the location of friendly forces and will contain tactical updates not available to the pilot. Pilots use maps in latitude and longitude designed to support air operations that do not include many of the features of the ground-focused version. Thus, the two maps have different reference bases that must be correlated.

5.3 Responsibilities

In artillery support missions, responsibility is shared between the forward observer and the gun crews. The forward observer is responsible for providing accurate target coordinates and corrections. The gun crew is responsible for putting rounds on the designated location. If there is an error, a short round for example, responsibility is assigned accordingly. On CAS missions, responsibility is not shared, it is transferred—different organizations and, sometimes, different services are involved. In the U.S. armed forces, only the U.S. Marine Corps (USMC) has an organic fixed-wing CAS capability. The U.S. Army has organic rotary-wing CAS assets, but depends on the U.S. Air Force for fixed-wing CAS. With the exception of the USMC, organic vs. nonorganic support is a major issue, and the services involved typically do not assume mutual responsibility.

5.4 Command and Control

Even though a gun crew that responds to a forward observer may be unknown to him and organizationally detached, from his perspective, the crew is responding directly to his command. In reality, there are a number of intervening levels that exercise command and control, which include the assignment of the observer's request to a particular gun. Command and control is by exception. Intervention occurs only when a problem is perceived; otherwise, approval is automatic. On CAS missions, command and control can be similar. Forward air controllers have authority for all CAS missions in their assigned area of responsibility, and higher command levels intervene only under unusual circumstances.

6. UAV/UCAV APPLICATIONS

Nontraditional operation and control concepts have the potential to not only enable unique new UAV and UCAV applications, but also to revolutionize ISR information production and dissemination. That is not saying that new concepts will supplant traditional concepts, rather that they could supplement them when quick-reaction, direct support of multiple users is required. As examples, CAS and ISR support of small units will be addressed.

6.1 CAS

The potential exists for UCAV to function as the virtual equivalent of long-range, organic artillery (Figure 6). This application has a number of advantages, one of which is the ability to provide quick-response, precision-fire support anywhere on the battlefield.

Artillery	UCAV
• Direct Fire Support Assigned to Ground Maneuver Unit	• UCAV Flight Assigned to Support Ground Maneuver Unit
• Fire Support Unit Positions to Cover Assigned Maneuver Unit	• UCAV Flight on CAP to Cover Assigned Maneuver Unit(s) (or on Strip Night at Forward Operating Base)
• Maneuver Unit Identifies/Locates Target (UTM Reference), Requests Fire Support	• Maneuver Unit Identifies/Locates Target (UTM Reference), Requests CAS
• Forward Observer (FO) Receives/Reviews Request	• FO/FAC Receives/Reviews Request
• FO Geolocates Target, Tasks Fire Support Unit (Digitally)	• FO/FAC Geolocates Target, Transmits 9 Line Message (Digitally)
• Target Assigned to Gun Crew (Digitally)	• Target Assigned to UCAV, Released for Mission (By UCAV Operator)
• Cut Charge, Load, Fire One • Adjust Fire • Fire for Effect	• UCAV Reports Inbound, Confirms IP and Weapon Target Coordinates • FO/FAC Confirms/Adjusts Target, Weapon Release Authorized

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Figure 6. UCAV Artillery Analog

6.1.1 Tasking

UCAV air vehicles would either sit-strip alert or loiter above the battlefield while awaiting requests for fire support. Forward observers would generate requests for support using standard preformatted artillery fire support messages. Like the "pizza delivery" analog, a universally available standard tactical radio would be used to place the order. Fire support requests would identify observer, friendly and target GPS locations, and attack direction plus other standard targeting information. Requests would be sent to an artillery fire control center and forwarded to a supporting UCAV unit when distances involved exceed available artillery capabilities. An automated taxi dispatch-like system could be used to task the UCAV network.

6.1.2 Operator Control

Upon receipt or acceptance of an air support assignment, a UCAV operator would designate an air vehicle (or strike package) to respond and immediately send it toward the target area. While enroute, the operator would use automated planning tools to generate a detailed mission profile that includes routing to avoid threats and/or friendly air operations. An updated plan would then be transmitted to the enroute UCAV along with an access code to allow the forward observer to assume limited, local control when within line-of-sight (LOS). The UCAV operator would transition to a monitoring role when the forward observer authenticates his identity and assumes local control responsibility.

6.1.3 Limited Local Control

Upon initial contact, the UCAV would transmit a digital message describing its mission, weapons load, designated target, etc. (Figure 7). Target location would either be in the form of GPS coordinates displayed on a digital tactical map and/or as a target image from an onboard UCAV sensor. The forward observer would either confirm the target/mission as received and authorize weapon release, call off the attack, or update or refine the target. In the last case, the UCAV would repeat the new information back to confirm targeting prior to weapon release. After the attack, the UCAV could be directed to provide bomb damage assessment information and/or re-attack under local control. As a result of the artillery-based operation and control concept, artillery-like response times are projected (Figure 8). Responsiveness would be a function of platform speed, altitude, and distance to target. A CAS UCAV with fighter-like speed capabilities and delivery profiles, therefore, could match artillery for weapons time on target.

6.1.4 Hand Back

Upon successfully completing its mission, the forward observer would notify the UCAV operator, who could either return it to base or assign it in another CAP location. Note that while the forward observer assumed limited control, the UCAV operator monitored the vehicle and could reassume control if required. This would allow the forward observer to concentrate on his mission (putting weapons target) and eliminate any requirement to deal with UCAV system-unique demands.

6.1.5 Benefits

In addition to artillery-like response times, a number of benefits accrue (Figure 9). Most of them are enabled by the fundamental concept of limited local control during the attack phase. The need for lengthy coordination between air and ground participants is effectively eliminated. The anxiety level and potential for errors drops accordingly.

6.2 Reconnaissance

A similar approach could allow individual ground units to task UAVs for ISR support and information dissemination. A local maneuver unit, for example, could generate a request for imagery or surveillance support of ground operations. If up-to-date imagery was not resident in a database, the request could be sent to an appropriately located UAV to point its sensors at a designated target and respond with imagery or an update of the local tactical environment. If no UAV was in position, with sufficient priority, one could be instructed by its operator to alter its flight path. In either case, the role of the UAV operator would not be to control the sensors or fly the UAV, but rather to service the user requests, assign them to the most appropriate asset for execution, and ensure timely responses against stated user requirements.

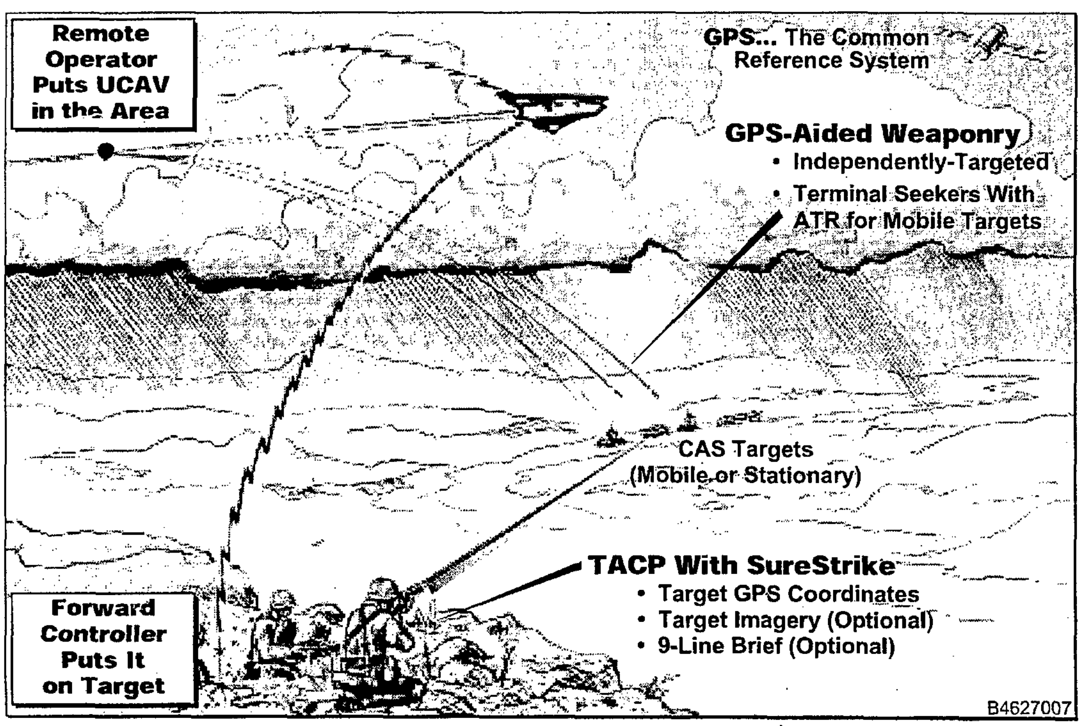

Figure 7. UCAV "Airborne Artillery"

Assumptions

- **IP to Target – 5 n.mi**
- **UCAV TAS – 540 kt**
- **Weapon Release From 15 K'**

Event	Elapsed Time (Sec) From CAP @ 10 nm	25 nm	50 nm
• FO/FAC Receives Fire Support Request (Digital)	00	00	00
• 9 Line Message Xmit	15	15	15
• UCAV Assigned, Released From CAP	25	25	25
• Mission Planned/Authorized (UCAV Operator)	50	50	50
• UCAV Released to FO/FAC	55	55	55
• UCAV Reports Inbound	55	55	55
• IP and Target Coordinates Confirmed	70	70	70
• 10 Sec From IP, Cleared for Weapon Release	80	180	350
• Weapon Release (From 15k')	100	200	370
• Weapons on Targets	130	230	400
• Available for Reattack	165	265	435
• Next Weapon on Target	195	205	495

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Figure 8. UCAV CAS Timelines

- **Reduce Number of People Involved**
  - **Theoretical Minimum = 1 (During Attack)**
- **Minimize Number of Organizations Involved**
  - **Theoretical Minimum = 1 (At Any Given Time)**
- **Reduce Anxiety Level**
  - **FO/FAC In Charge of Attack**
- **Minimum Communication Time**
  - **Single Burst Transmissions(s) From Ground-to-Air**
  - **Single Burst Confirmation From Air-to-Ground**
- **Provide Single Ground Reference System**
  - **Standard Map**
    and/or
  - **High Resolution Image**

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Figure 9. CAS UCAV Benefits

Unlike the CAS example, however, response times would not be driven as much by platform speed and distance to target. A standoff UAV within line of sight would be able to image the target at the speed of light, assuming its sensors have sufficient resolution at the distances involved and that bandwidth was adequate.

7. USER-CONTROLLED AIR VEHICLE SYSTEM CONCEPT

A logical extension of the UAV operation and control concepts and information processing and dissemination discussed previously is a universally accessible system for all unmanned air assets positioned over the battlefield to support multiuser needs. We will describe this as a User-Controlled Air Vehicle System, but will refrain from using an acronym to describe it. Instead, we will use the term StrikeNet, a LM implementation of this basic system concept. In our vision, StrikeNet would support multiple users at multiple locations and involve multiple services, weapons, and platforms including SOWs (Figure 10). It would be enabled by the concept of network-centric warfare, in which all battlefield participants are able to exchange digital information with and gain access to whatever information source is necessary to accomplish their mission. It would, however, not have to wait for full implementation of the network. The system would be based on a modular, open architecture and could use any existing tactical datalink and/or modem to transmit or receive digital data. Connectivity could be established wherever communication links exist; performance would simply vary with available bandwidth. Because the system concept is based on communicating by short-burst digital instructions or responses and (preferably) freeze frame sensor images, required bandwidth would be minimized.

7.1 Applications

StrikeNet would make the unmanned air assets of the battlefield available to all appropriately validated users (Figure 11). In addition to the lethal missions already discussed, StrikeNet could be tasked to provide and disseminate situation awareness data to any user regardless of location. This could include tank and other mechanized equipment drivers who could request and receive the same quality and quantity of real-time information in the cockpit as fighter, bomber, and helicopter pilots. Evacuees could send tactical status information to rescue forces so that air drops of supplies could be requested and locally coordinated. Like the Internet, once the basic concept is developed and enters use, unanticipated applications will follow.

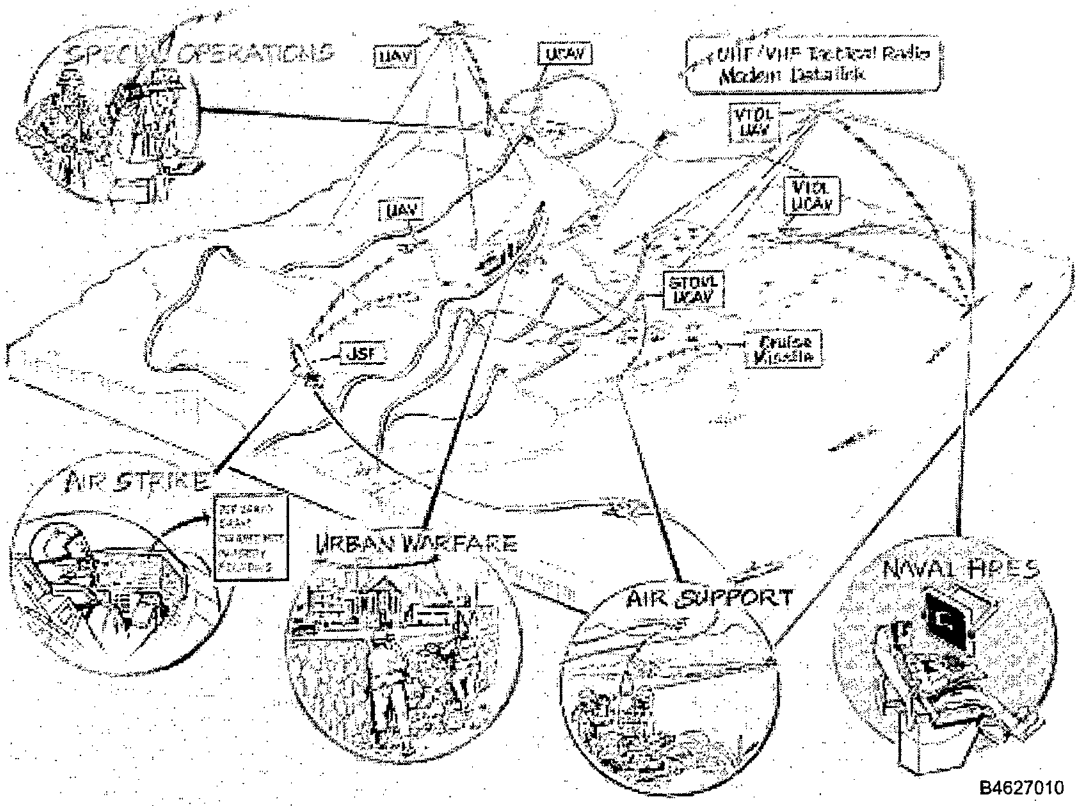

Figure 10. LM StrikeNet User-Controlled Air Vehicle System Concept

- **Close Air Support**
  - **Virtual Equivalent of Organic Long Range Artillery**
- **Real Time Intelligence in "Cockpit"**
  - **Surveillance / Control Platforms**
  - **Fighters**
  - **Bombers**
  - **Helicopters**
  - **Mechanized Equipment**
  - **Command Posts**
- **"Tight" ROE Situations**
  - **Urban Operations**
  - **Special Operations**
  - **Rescue Operations**
- **Other**
  - **Standoff / Support Jamming**
  - **Payload Delivery**
  - **Perimeter Defense**
  - **Etc.**

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Figure 11. LM StrikeNet System Applications

7.2 Benefits

A number of benefits are associated with the overall StrikeNet system concept (Figure 12). Included is the potential to reduce proliferation of individual UAV types to support individual users. Guaranteed access to a UAV network could be a more cost-effective option. Some high-priority users such as U.S. Special Operations Command (SOCOM) have even stated that they have no interest in owning or operating UAVs; they only want to use them[6].

7.3 Challenges

Although the StrikeNet concept is based on using available datalinks and/or modems and other system elements, there still will be a number of challenges associated with development and implementation. The challenges cover issues ranging from communications system compatibility through air vehicle design.

7.3.1 Communications

The battlefield is replete with service, system, and user-unique communications channels, frequencies, and formats. No existing tactical transceiver is compatible with the full range of UAV transmitters and receivers (Figure 13). Fortunately, potential solutions are under development to include the Joint Tactical Control System (TCS), the DOD Digital Modular Radio, and other multifunction digital tactical transceivers. TCS is perhaps the most directly applicable since it is intended to provide a universal control and information dissemination capability for all UAVs and control stations. It also is intended to be compatible

- **Universal Access to Unmanned Air Support Assets**
  - **Situation Awareness**
  - **Weapons on Target**
  - **Payloads on Target**
- **Direct Support of Maneuver Units (Sea / Land / Air)**
  - **Virtual Equivalent of Organic Air Assets**
  - **No "Visible" Intermediaries**
  - **SA Update Included at Minimal Additional Cost**
- **Efficient Dispatch of Incoming Requests**
  - **Quick Pairing of "Targets" and "Shooters"**
- **Efficient Dissemination of Tactical ISR Data**
  - **Direct Pipe From Sensor to Shooter**
- **Existing/Planned Assets In Robust Network Centric Tactical Architecture**
- **Alternative to Continued Unmanned Air Vehicle Type Proliferation**

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Figure 12. LM StrikeNet Benefits

with existing tactical data networks such as the Advanced Targeting Handoff System. While these systems are under development, however, there are existing systems and protocols such as the improved data modem (IDM) that exist in credit card-size, plug-in modules and that can support a limited initial operational capability. And even though the essence of the system described herein is line-of-sight controlled by local users, over-the-horizon connectivity with UAV and UCAV controllers and their command and control systems will still be required.

7.3.2 Command and Control

Another challenge for the StrikeNet system concept will be development of a command and control system that gives individual users easy access and provides timely and systematic responses. Low-priority users, for example, cannot be allowed to divert a UAV that is positioned to meet higher priority requirements. UAVs also cannot be allowed to wander aimlessly about the battlefield in response to multiple user requests. A prioritized user-request service system will need to be developed to manage the available assets and maximize overall system effectiveness. A candidate approach could be based on the COTS automated taxi dispatch system previously described. There are also a number of "sensor to shooter" concepts under development that could be adapted for the StrikeNet system concept.

7.3.3 Security

Universal ["Own Force"] accessibility, the essence of the StrikeNet system concept, also makes it a system security challenge. These challenges, however, are not unique. For example, the joint situation awareness datalink is intended to provide friendly forces with full awareness of friendly and enemy positions on the battlefield. Confining this information to validated

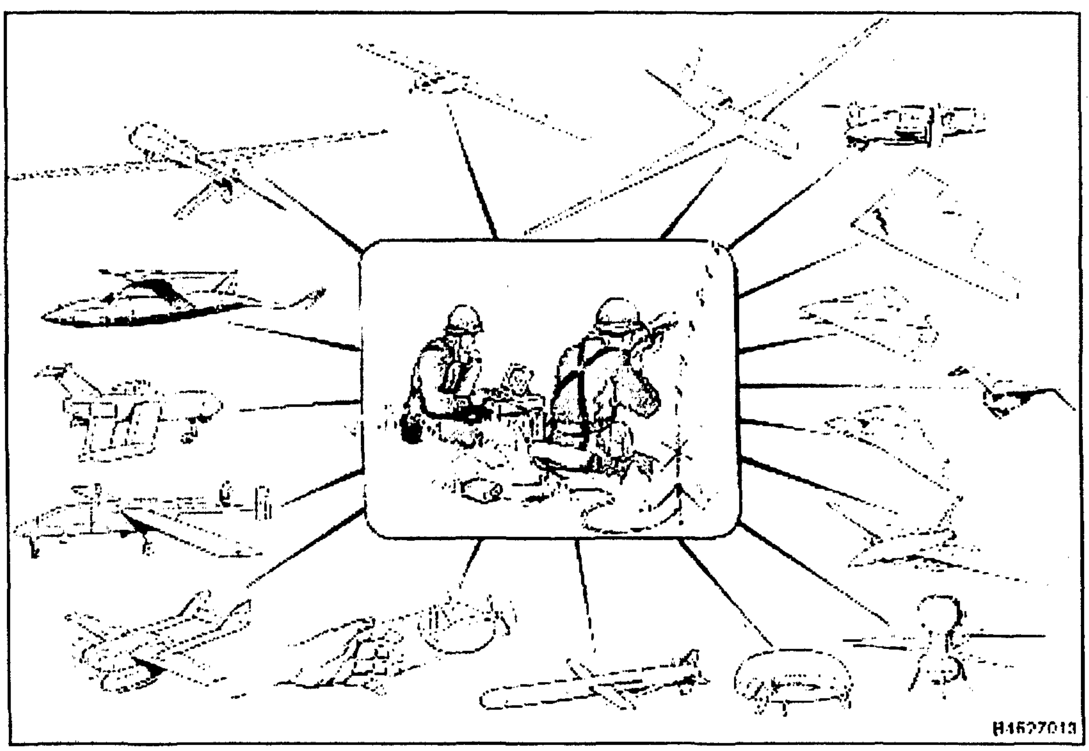

Figure 13. StrikeNet Communication Challenge

friendly users is no less challenging. In fact, the whole concept of network-centric warfare faces these challenges. Solutions include a number of well-developed approaches (e.g., secure authentication codes plus new and innovative technology). For example, StrikeNet will make extensive use of GPS for target and friendly force identification. User GPS locations, therefore, could be correlated with known or projected friendly locations and add an additional measure of security. In addition, COTS-developed facial and eye recognition could be employed to authenticate system users.

7.3.4 Air Vehicle Compatibility

The size and speed of development of the modern battlefield will be a StrikeNet challenge for the air vehicle (Figure 14). Air vehicles will probably operate in one of two modes while awaiting tasking, sitting strip alert, or flying CAP. The former mode will require a vehicle designed to operate from forward airfields and may require short and/or vertical takeoff and landing capabilities. The other mode will require air vehicles that can loiter efficiently and still respond quickly to time-critical needs at significant distances from their CAP position. Although contemporary UAVs are optimized for endurance, they have limited speed and maneuverability. Some, in fact, would have difficulty keeping up with mechanized ground units. A new class of air vehicle, therefore, will probably be required, one with fighter-like speed and tactical flexibility and bomber/transport-like cruise and loiter efficiency. The result could be an unmanned equivalent of the World War II medium-bomber concept. Finally, payload requirements and survivability will also drive air vehicle design. If UCAVs are required to carry current inventory vs. miniature weapons, for example, by definition they will not be small vehicles. If they are required to survive for long periods in hostile tactical environments, they will need compatible observables and/or survivability/defensive features. Integrating all these capabilities into a single air vehicle type will be no small challenge.

7.4 Recommended Approach

Lockheed Martin envisions a systematic approach to developing StrikeNet or equivalent system concepts. First, user communities should evaluate the concept and determine if it is consistent with their vision of the future scope and direction of tactical warfare. If so, CONOPS evaluation and experimentation should be undertaken by service battle labs. Industry could support the evaluations with modeling and simulation capabilities such as the LMTAS Man-in-the-Loop UCAV System Simulator. Combined operation exercise experiments using surrogate system elements could follow to verify simulation results. Finally, system-level concept studies could be initiated to develop candidate system-level solutions, technology needs and an orderly concept, and system development plans.

8. CONCLUDING REMARKS

The technology exists to enable evaluation, design, and development of a user-controlled air vehicle system that can provide individual combat users with access to and control of networks of UAVs. The key issues associated with the system concept are operational in nature and can be evaluated in simulation (constructive and man-in-the-loop) and in field experiments (using surrogates). Upon favorable evaluation of the concept, additional technologies could be developed to enhance the system concept. Included are automatic target recognition (ATR) to cue users to tactical developments, advanced data compression to improve response times, and multisource correlation to provide multiple users with tactical situation awareness previously available only to senior commanders.

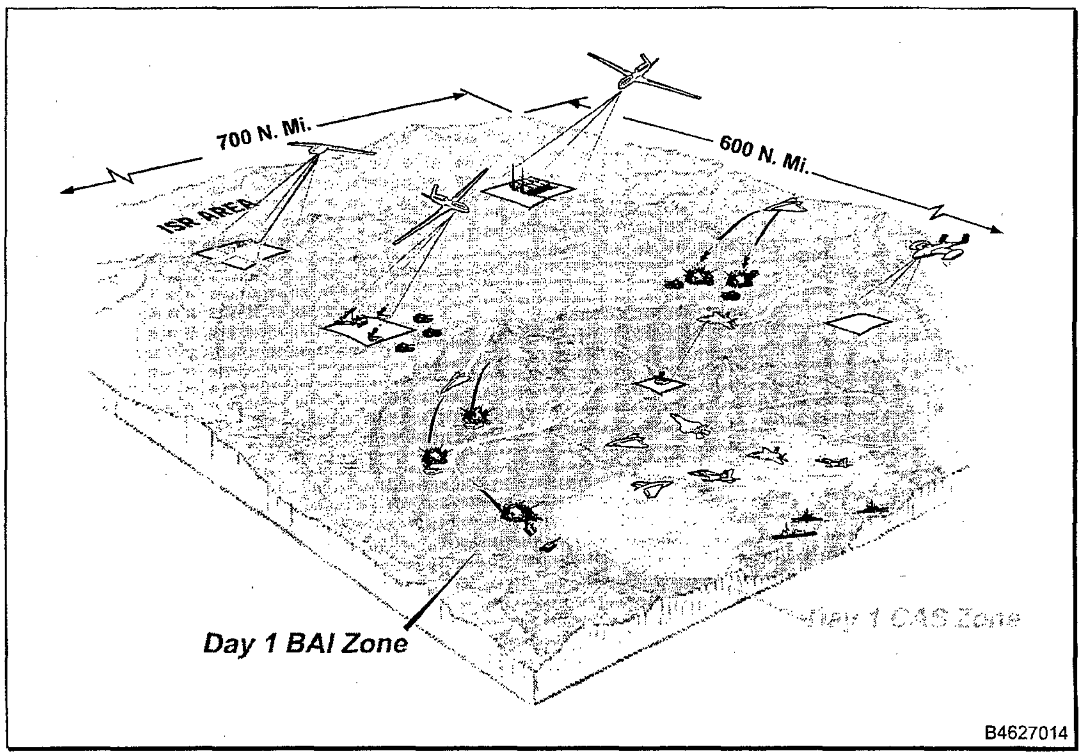

Figure 14. StrikeNet Operational Area Challenge

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10. ACKNOWLEDGEMENTS

The support of the following individuals who provided invaluable insight and support is gratefully acknowledged:

Dr. John V. Kitowsky, Systems Engineering; Mr. Mark Witte, Configuration Development; Mr. Steve Weigel, Weapon System Integration; Mr. Ed Brungardt, Information Warfare; Mr. Allan Hill, Support System Integration; Mr. Pruitt Benson, Configuration Development; Ms. Jean Fox, Configuration Development; Mr. Scott Anderson, Illustrations; Ms. Christy Crowell and Ms. Sherri Ray, Proposal Development Center.

REPORT DOCUMENTATION PAGE

1. Recipient's Reference	2. Originator's References	3. Further Reference	4. Security Classification of Document
	RTO-MP-44 AC/323(SCI)TP/17	ISBN 92-837-0011-2	UNCLASSIFIED/ UNLIMITED

5. Originator Research and Technology Organization
North Atlantic Treaty Organization
BP 25, 7 rue Ancelle, F-92201 Neuilly-sur-Seine Cedex, France

6. Title

Advances in Vehicle Systems Concepts and Integration

7. Presented at/sponsored by

the Systems Concepts and Integration Panel (SCI) joint symposium covering: Symposium (A) on "Aircraft Update Programmes. The Economical Alternative?" and Symposium (B) on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles" held in Ankara, Turkey, 26-28 April 1999.

8. Author(s)/Editor(s)	9. Date
Multiple	April 2000

10. Author's/Editor's Address	11. Pages
Multiple	400

12. Distribution Statement There are no restrictions on the distribution of this document. Information about the availability of this and other RTO unclassified publications is given on the back cover.

13. Keywords/Descriptors

Symposium A

Upgrading	Detectors
Fighter aircraft	Aircraft engines
Rotary wing aircraft	Avionics
NATO forces	Integrated systems
Cost effectiveness	Transport aircraft
Service life	Man machine systems
Defense economics	Lessons learned
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Human factors engineering	Critical technologies	Distributed systems
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Man computer interface	Missions	Drone vehicles
UAV (Unmanned Aerial Vehicle)	Battlefields	

14. Abstract

The meeting proceedings from this joint symposium on "Advances in Vehicle Systems Concepts and Integration" contain the Technical Evaluation Reports and papers presented at Symposium (A) on "Aircraft Update Programmes, The Economical Alternative?" and at Symposium (B) on "Warfare Automation: Procedures and Techniques for Unmanned Vehicles". It was organized by the Systems Concepts and Integration (SCI) Panel of the RTA in Ankara, Turkey from 26 to 28 April 1999.

Symposium (A) was structured in five sessions covering Cockpit, Sensors, Engine, Overview and Lessons Learned (Part I and Part II) and was concluded by a panel discussion.

Symposium (B) was structured in four sessions covering Operational requirements for unmanned vehicles, Integration aspects and mission management, Platform management and critical technologies and System concepts and mission experience.

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Imprimé par le Groupe Communication Canada Inc.
(membre de la Corporation St-Joseph)
45, boul. Sacré-Cœur, Hull (Québec), Canada K1A 0S7

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Printed by Canada Communication Group Inc.
(A St. Joseph Corporation Company)
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ISBN 92-837-0011-2